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QUANTITATIVE MICROSCOPIC ANALYSIS[1]

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ABSTRACT

After outlining briefly the quantitative methods of Delesse, Rosiwal, Johannsen, Shand, and Wentworth, as carried out on mineral surfaces or thin-sections, the paper deals with some new variations of the Rosiwal method. These are based on the fundamental principle that accuracy of quantitative determination is increased by enlarging the scale of measurement or estimation. To this end small cross-sectioned grids, so arranged that one square of the grid corresponds to 1 per cent of the total area, are superimposed on photomicrographs or lantern slides. Quantitative determinations are then made either by areal estimation or lineal measurement. To increase the scale of measurement still farther, determinations are also made on the images of lantern slides, as projected by the lantern on the screen. The accuracy of these three new methods is checked successfully against a photographic variation of the Delesse method. A more rapid method for approximate determinations is also evolved by setting up a series of quantitative photographic standards, by comparison with which determinations may be made on any section. These standards are given for five of the common structures in ores. Finally there are indicated a few of the directions in which such quantitative methods may be used.

INTRODUCTION

Qualitative microscopic determination of transparent rock-forming minerals has developed steadily since the days of Sorby, when thin-sections were first used. In more recent years the microscopic study of the opaque ore minerals, though still hampered by inaccuracies and indecisive results, has been brought to the stage where the commoner ore minerals may be determined with reasonable accuracy. On the other hand, quantitative methods, though developed

[1] The work on which the paper is based was started in the Laboratory of Economic Geology, Harvard University, under the supervision of Professor L. C. Graton, and continued in the Laboratory of the Department of Mineralogy, University of Toronto.

in some detail by different workers, have not found favor with most microscopic petrographers and have scarcely ever been used by the mineragrapher. Either it was considered that, in view of the degree of accuracy shown by the results obtained, the methods proposed consumed too much time, or the tediousness of the process of counting, even with the aid of mechanical devices, discouraged the investigator from using this avenue of approach.

For the last eighty years petrographers, both in Europe and on this continent, have felt the need of a correct classification of the igneous rocks on a quantitative mineralogical basis. Various methods have been developed from time to time for the accomplishment of this object. Up to the time when Delesse[1] first outlined a definite scheme for geometrical analysis, the quantitative ratios of the individual minerals to the rock as a whole were obtained by the laborious and lengthy process of separating individual minerals for individual analyses or, in the case of a simple rock of but two mineral constituents, for a determination of the density of the mineral constituents. These methods were of very limited application and never came into common practice. Delesse was the first to enunciate the principle that the volumetric might be related to the areal proportions, provided enough area was included in the determination to take care of the third dimension. Delesse's quantitative determinations were carried out on a polished or flattened hand-specimen, on which transparent paper and lead or tinfoil was applied. The mineral outlines were marked on the paper, which, with the foil, was afterward cut out and weighed.

Sorby[2] and Sollas[3] used modifications of the Delesse method with the camera lucida as an extra bit of equipment to aid in quantitative determinations.

By far the greatest single contribution to the quantitative side of petrography was furnished by A. Rosiwal[4] in 1898, whose classic work has served as a model for all investigators up to the present

[1] A. Delesse, *Annales des Mines*, 4th Ser., Vol. XIII (1848), pp. 379–88.

[2] H. C. Sorby, *Phil. Mag.*, 4th Ser., Vol. XI, p. 21.

[3] W. J. Sollas, *Trans. Royal Irish Academy*, Vol. XXIX, Part 14, p. 471.

[4] A. Rosiwal, "Über geometrische Gesteinsanalysen. Ein einfacher Weg zur ziffermässigen Feststellung des Quantitatsverhältnisses der Mineralbestandtheile gemengter Gesteine," *Verhandl. der K. K. Geol.* (Reichsanstalt, 1898).

day. The essence of the Rosiwal method of quantitative determination was the reduction of the volumetric ratio of the individual constituents to a single dimension, as first suggested by Delesse. The line, or series of lines cutting each other at right angles, that he used for this determination he called the "mass indicatrix." By actual experiment with blocks of both regular and irregular outline of known area dotted over his network of mass indicatrices, he was able to demonstrate that with a total length of indicatrix lines one hundred times the grain-size of the mineral constituents, it was possible to obtain accurate results within 1 per cent. His determinations were made partly with the aid of a tracing taken from the hand-specimen, but some at least were done on flattened or polished macroscopic specimens, by drawing the indicatrix lines on the surface of the rock and measuring directly along these lines.

Cross, Iddings, Pirsson, and Washington[1] used the Rosiwal method of lineal measurement to calculate the norm from the mode, illustrating by work on two thin-sections of Butte granite. In 1903 Joly[2] used a modification of the camera lucida Delesse method.

Not all investigators thought that Rosiwal's method of quantitative determination gave accurate results. Williams[3] states that "any one of the direct measurements with the microscope does not appear to fulfil even approximately the necessary conditions for a statement of the complete quantitative composition of an igneous rock such as granite."

Johannsen and Stephenson[4] analyzed carefully the determinations carried out by Williams and found his methods to be unjust in their application. In spite, then, of Williams' criticism of the Rosiwal method, it was used by many petrographers who found it the best means available up to that time for quantitative determination.

In 1911 Hirschwald[5] simplified the measurement in thin-sections

[1] *Jour. Geol.*, Vol. X, pp. 681–82.

[2] J. Joly, *Proc. Roy. Dublin Soc.*, Vol. X, pp. 83–84.

[3] Ira A. Williams, *Amer. Geol.*, Vol. XXV, pp. 34–46.

[4] A. Johannsen and E. A. Stephenson, *Jour. Geol.*, Vol. XXVII, pp. 216–20.

[5] J. Hirschwald, "Über ein neues Mikroskopmodell und ein Planimeter Ocular zur geometrischen Gesteinsanalyse," *Centralblatt für Min. etc.*, 1904, pp. 621–23; *Handbuch der bautechinischen Gesteinsprüfung*, 1912, pp. 146–47, 163–72.

by the use of a planimeter ocular. In 1914 Shand[1] introduced a recording micrometer device, which not only makes the measurements but also performs the addition of them. Johannsen published a paper in 1919[2] in which a scheme for quantitative measurement of a thin-section by planimeter is outlined. In 1923 Wentworth[3] introduced another recording micrometer of an improved type, by means of which it is possible to measure and record the quantitative proportions of several minerals simultaneously.

The results of the researches carried out by these investigators seemed to show that the Rosiwal lineal method, or modifications thereof, presented the best working principle for an accurate quantitative determination. It appeared, however, that the areal method could also be used to advantage in certain special cases and in particular where the degree of accuracy desired was not too high.

AREAL METHOD OF MEASUREMENT

With a view to testing the accuracy of this areal method, the writer conducted several preliminary experiments before deciding on the angle of attack to be used.

Two minerals of approximately the same specific gravity were selected. The minerals chosen for this purpose were pyrite (S.G. 4.95–5.10), and magnetite (S.G. 5.168–5.180). Through the kindness of Professor Charles Palache, of the Department of Mineralogy and Petrography of Harvard University, well-crystallized specimens of each mineral were secured. These were carefully ground, the impurities removed both by hand-picking and magnetic separation, and the powder screened to the sizes +20, +26, +35, +45, +55, +80, +110, +150, +200, −200 mesh. The two minerals in powdered form were then mixed thoroughly in different proportions by weight, such as 90:10, 80:20, 70:30, 60:40, 50:50, using 1-gram lots. They were then set in sealing-wax in a special brass holder,[4] and polished. Quantitative microscopic determination was then carried out by

[1] S. J. Shand, *Jour. Geol.*, Vol. XXIV, No. 4, pp. 394–404.

[2] A. Johannsen, *Jour. Geol.*, Vol. XXVII, pp. 276–85.

[3] C. K. Wentworth, "An Improved Recording Micrometer for Rock Analysis," *Jour. Geol.*, Vol. XXXI, pp. 228–32.

[4] E. Thomson, *Trans. C. I. M. and M.*, Vol. XXIX, pp. 281–86.

counting the grains of pyrite and of magnetite, using a microscope equipped with a special cross-sectioned eye-piece for purposes of orientation. Table I shows the deviations from the theoretical percentages and gives the maximum, minimum, and average errors for the different sizes from +20 to +110 mesh, as well as for all the sections examined, whether coarse or fine. A few of the sections were determined on the ground-glass screen of the metallographic microscope, and some duplicate determinations under the ordinary microscope were also included, making a total of sixty-eight determinations in all.

TABLE I

Size	No. Determined	Percentage		
		Maximum Deviation	Minimum Deviation	Average Deviation
20	9	−2.0	0.0	0.9
26	11	−3.7	−0.1	1.7
35	14	−4.2	0.0	2.3
45	10	−3.2	−0.3	1.7
55	14	−3.6	−0.1	1.7
80	5	−2.5	−0.8	1.5
110	5	−1.2	−0.5	0.9
All	68	−4.2	0.0	1.5

These results seem to indicate that, while the maximum deviation may be as high as 4.2 per cent, this is unusual; and the average deviation of but $1\frac{1}{2}$ per cent gives an idea of the accuracy of this method. It might be added here that those determinations carried out on the ground-glass screen of the metallographic microscope, where the factor of personal error should be a minimum, showed deviations as high as 2 per cent. It is likely, therefore, that at least part of the deviation amount in individual cases is to be attributed to the fact that the particular surface polished did not show the exact theoretical percentages as weighed out. This is not surprising as, no matter how thorough the mixing, there would naturally be some rearrangement of the individual particles in the process of mounting and polishing; and variations as high as 1 or 2 per cent from the theoretical values might reasonably be expected in a few instances.

In Plate I, Figures 1–5, the proportions 90:10, 80:20, 70:30, 60:40, and 50:50 are shown in selected fields of view for five of these mounts containing fragments of the two minerals in the +45 mesh size. These fields of view represent about one-fourth of the area contained within the brass ring and about one-sixteenth of the total surface of the mount. The proportion of sealing-wax, which is roughly about 60 per cent of the total area, was disregarded in these quantitative determinations, the total of 100 per cent being made up of the metallic constituents only. It will be noted that in two of the five cases cited the proportions of the two constituents vary 2 per cent from the theoretical values. It seemed quite superfluous to include illustrations of the other sizes, as they show identical relations and differ only in size of fragments and proportion of sealing-wax. The +45 mesh size was selected as being about halfway between the coarse and the fine sizes. By decreasing the magnification for the coarser and increasing it for the finer, identical pictures may be obtained for the other screen-sizes. This phase of the investigation may be of interest to mill men as indicating a rapid and approximate method of determining the quantitative relations obtaining in any of the fragmental products such as concentrates or tailings. Comparison may be made with these standards, and results sufficiently accurate for most purposes obtained in a very short while. This method may be used not only for the coarser but also for the extremely fine sizes. The writer has prepared such fragmental mounts up to −300 mesh size, both for concentrates and for tailings, using the small brass ring without the enclosing rectangular brass container and stripping off even the brass ring, after the wax cement had hardened, before polishing.

Most of these determinations were carried out with an ordinary microscope equipped with a cross-sectioned eye-piece. This induced eye-strain, and undoubtedly part of the deviation might quite properly be attributed to the inaccuracy in counting arising therefrom.

PHOTOMICROGRAPHIC MEASUREMENT

To eliminate this factor of eye-fatigue as far as possible, it was decided to remove the counting from the microscope altogether, increasing the size of the field of view and consequently the apparent

PLATE I

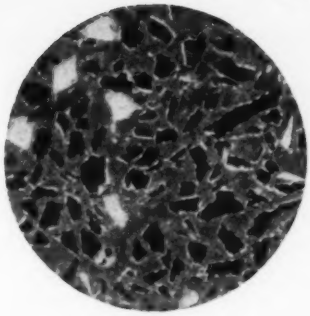

FIG. 1

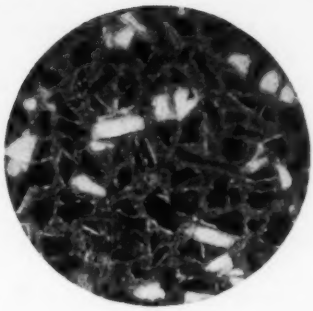

FIG. 2

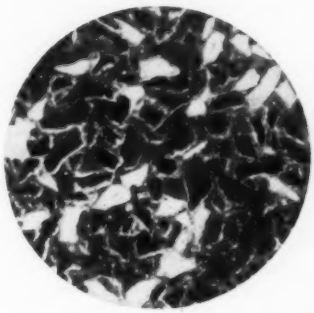

FIG. 3

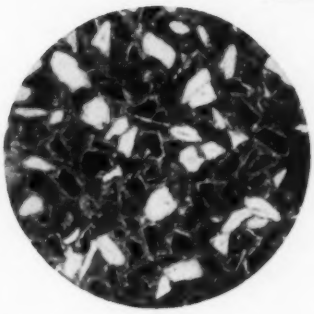

FIG. 4

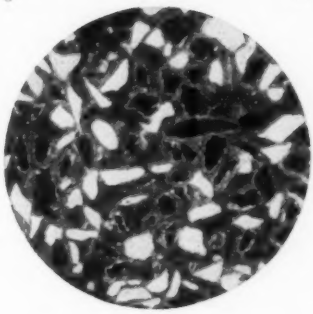

FIG. 5

FIG. 1

Black, magnetite	89% (90)*
White, pyrite	11% (10)
Gray, sealing-wax	
Size, 45 mesh	
× 10	

FIG. 2

Black, magnetite	79% (80)
White, pyrite	21% (20)
Gray, sealing-wax	
Size, 45 mesh	
× 10	

FIG. 3

Black, magnetite	70% (70)
White, pyrite	30% (30)
Gray, sealing-wax	
Size, 45 mesh	
× 10	

FIG. 4

Black, magnetite	58% (60)
White, pyrite	42% (40)
Gray, sealing-wax	
Size, 45 mesh	
× 10	

FIG. 5

Black, magnetite	48% (50)
White, pyrite	52% (50)
× 10	

*Figures in parentheses, theoretical; those not in parentheses, experimental.

size of the mineral fragments. Photomicrographs or lantern slides seemed to furnish good media for this purpose, the magnification used being adapted to the size of the particles. Only reproductions of polished sections of ores were used; but the method is equally well

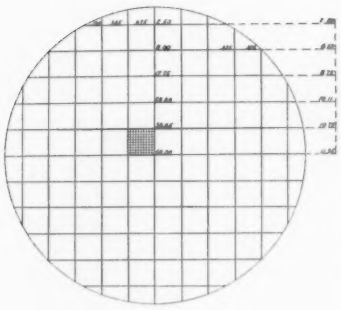

FIG. 6

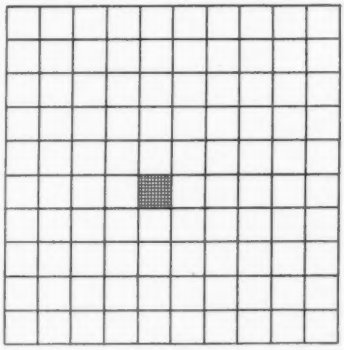

FIG. 7

suited to a quantitative determination of the transparent minerals in thin section, provided the individual constituents are clearly marked out from their neighbors.

MEASURING GRIDS

Cross-sectioned grids were next devised for this quantitative determination. These were of three types, as illustrated by Figures 6–8. For convenience of computation by the areal method, each of the grids was so arranged that one square or one segment represented 1 per cent of the total area, thus giving results directly in percentage values. The circular grids were made in three sizes, 5, 6, and 7 cm. diameter, to accommodate the usual dimensions of photomicrographs, and were of two distinct types: one divided

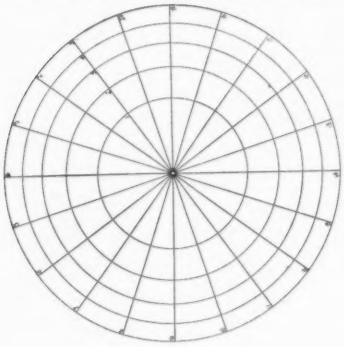

FIG. 8

into squares and the other into segmented annular rings. On experiment the latter type was found unsatisfactory and was discarded in favor of the former. The square grid was made 5 cm. square and was found to be particularly well adapted to the lineal method as, by using ten right and left measuring lines, and ten fore and aft, the percentage value was obtained direct. Lantern slides were then made

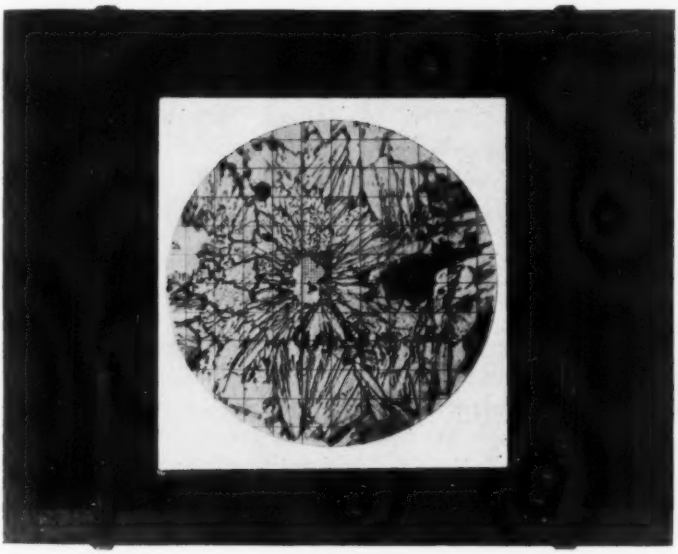

FIG. 9

of these grids, and the photomicrographic prints were placed between the lantern slide of the grid and an extra cover glass with an elastic band to hold all together (Fig. 9). Experiments were carried out on photographs of polished sections and were found to be satisfactory. Where it is desired to make a quantitative determination without the rather lengthy and costly photomicrographic process, excellent results may be obtained by using similar square grids on a ground-glass plate, substituted for the regular focusing plates of the metallographic outfit. The writer has been able to apply this variation of the method to commercial ores from British Columbia, both in the solid

and the fragmental form, with very good success, using the lineal type of measurement throughout.

Through the kindness of Professor Graton, of the Department of Economic Geology, Harvard University, the writer was able to secure photomicrographs of a wide variety of ores, showing such common structures as granular, island and sea, vein, radiating, graphic, and grating. These were printed with a field of view corresponding exactly to the circular grid of 5 cm. diameter. In all, 103 such photomicrographs were first used and the proportions of the different mineral constituents estimated by the areal method. Of these, 5 consisted of mixtures of pyrite and chalcopyrite with some associated quartz gangue, where the differences of relief induced by the polishing process made the exact estimation of the mineral boundaries impossible. The results from these specimens were therefore discarded as of no significance.

LINEAL MEASUREMENTS

Of the remaining 98, 56 had the proportions computed also by the lineal method, using the same 5 cm. circular grid and measuring in millimeters along two sets of eleven lines, one set at right angles to the other. The figures thus obtained showed remarkably close agreement with the results obtained from the areal measurement, except in cases where the individual mineral fragments were widely scattered, irregular in outline, and, in general, smaller, at the magnification used, than the square measuring units. In 22 cases the results obtained by the lineal method were higher; in 33 cases they were lower; while 1 specimen gave identical results by the two methods. The maximum difference noted in the two sets of results was 8.3 per cent, the lineal method giving a higher result than the areal. The average difference for the 56 determinations, disregarding the plus or minus sign, was 2.3 per cent. By analyzing these results still farther, it was found that 31 of the determinations, or 55.3 per cent, showed differences either below or at the average (2.3 per cent); 9 of them, or 16.1 per cent, showed differences below 3 per cent and above 2.3 per cent; and the remaining 16, or 28.6 per cent, differences above 3 per cent. All of the 16 showing differences greater than 3 per cent

were of the small scattered, irregular type mentioned above, where the estimation of the number of squares occupied by any one mineral was of necessity but approximate in character. For such cases the lineal method is recommended, and for ease of calculation the square instead of the circular grid should be used.

In order that a set of quantitative standards might be established for more approximate determinations, photomicrographs were prepared for each of the five common structures: granular, graphic, grating, island and sea, and vein, giving proportional relations from 5–95 to 50–50 per cent, in intervals as close to 5 per cent as possible. These are shown in Plates II–VIII in the 5 cm. size. It will be noted that for two of the structures but 7 standards have been prepared, with somewhat greater intervals between than for the other three structures with 8 or 9 standards. After many determinations, carried out on about 150 photomicrographs, it was found necessary to effect this compromise for the two structures indicated.

To demonstrate the accuracy of this variation of the quantitative method, determinations of percentages of minor constituents were made independently by two of the writer's colleagues, on two photomicrographs of sections showing granular and vein structures, using the method of comparison with the standards shown. In each case the results obtained were within 2 per cent of the predetermined values. So that the reader may test his own skill in this type of quantitative determination, the two photomicrographs used for this experiment are shown in Figures 15 and 16. The percentages of the minor constituent in each section, as determined by the lineal method, are given in a footnote at the bottom of page 213. Similar standards for other structures, such as the radiating or mutual, may easily be established by other investigators; and it is to be hoped that these illustrations may but serve as guides along the way to future research in the quantitative field.

The limitations of the lineal method are fixed by the measurability of the individual mineral intercepts and the number of them per measuring line. It is much more difficult to measure accurately in millimeters than in centimeters, or in inches rather than in feet, while ten slightly inaccurate measurements on a measuring line affect the final result far more than one measurement of the same character.

EXPLANATION OF PLATES II TO VII

Plate II

Fig. 10*a*.—White, chalcopyrite	5%	Granular structure
Light gray, pyrrhotite	95%	× 100
Dark gray, sphalerite		
Black, gangue		
Fig. 10*b*.—White, chalcopyrite	9%	Granular structure
Gray, pyrrhotite	91%	× 100
Black, gangue		
Fig. 10*c*.—Dark gray, sphalerite	16%	Granular structure
Light gray, pyrrhotite	84%	× 100
Black, gangue		
Fig. 10*d*.—Dark gray, franklinite	21%	Granular structure
Light gray, magnitite	79%	× 250
Black, gangue		
Fig. 10*e*.—Light gray, magnetite	26%	Granular structure
White, chalcopyrite	74%	× 140
Black, gangue		
Fig. 10*f*.—White, chalcopyrite and pyrrhotite	31%	Granular structure
Dark gray, gangue	69%	× 140

Plate III

Fig. 10*g*.—Dark gray, franklinite	36%	Granular structure
Light gray, magnetite	64%	× 250
Black, gangue		
Fig. 10*h*.—Light gray, pyrrhotite	40%	Granular structure
Dark gray, sphalerite	60%	× 100
Black, gangue		
Fig. 10*i*.—Light gray, magnetite	52%	Granular structure
White, chalcopyrite	48%	× 140
Black, gangue		
Fig. 11*a*.—Dark gray, bornite	4%	Graphic structure
Light gray, chalcocite	96%	× 100
Black, gangue		
Fig. 11*b*.—Dark gray, bornite	10%	Graphic structure
Light gray, chalcocite	90%	× 100
Fig. 11*c*.—Dark gray, bornite	16%	Graphic structure
Light gray, chalcocite	84%	× 290
White, pyrite		
Black, gangue		

Plate IV

Fig. 11*d*.—Dark gray, tennantite	19%	Graphic structure
Light gray, pearcite	81%	× 330
Black, gangue		
Fig. 11*e*.—Light gray, chalcocite	25%	Graphic structure
Dark gray, bornite	75%	× 100
Fig. 11*f*.—Dark gray, bornite	28%	Graphic structure
Light gray, chalcocite	72%	× 290
Fig. 11*g*.—Dark gray, bornite	34%	Graphic structure
Light gray, chalcocite	66%	× 100
Fig. 11*h*.—Light gray, chalcocite	40%	Graphic structure
Dark gray, bornite	60%	× 100
Black, gangue		
Fig. 11*i*.—Light gray, chalcocite	45%	Graphic structure
Dark gray, bornite	55%	× 100
Black, gangue		

Plate V

Fig. 12*a*.—White, chalcopyrite	6%		Grating structure
Gray, bornite	94%		× 100
Black, gangue			
Fig. 12*b*.—White, chalcopyrite	10%		Grating structure
Gray, bornite	90%		× 100
Black, gangue			
Fig. 12*c*.—White, silver	14%		Grating structure
Gray, dyscrasite	86%		× 150
Black, gangue			
Fig. 12*d*.—Dark gray, bornite	21%		Grating structure
Light gray, chalcocite	79%		× 100
Black, gangue			
Fig. 12*e*.—Dark gray, bornite	28%		Grating structure
Light gray, chalcocite	72%		× 100
Black, gangue			
Fig. 12*f*.—White, matildite	35%		Grating structure
Black, galena	65%		× 150

Plate VI

Fig. 12*g*.—Light gray, white chalcocite	40%		Grating structure
Dark gray, blue chalcocite	60%		× 290
Fig. 13*a*.—Dark gray, bornite	7%		Island and sea structure
Light gray, chalcocite	93%		× 100
Black, gangue			
Fig. 13*b*.—White, chalcopyrite	11%		Island and sea structure
Gray, chalcocite	89%		× 100
Black, gangue			
Fig. 13*c*.—White, chalcopyrite	16%		Island and sea structure
Gray, chalcocite	84%		× 100
Black, gangue			
Fig. 13*d*.—White, pyrite	22%		Island and sea structure
Gray, chalcopyrite and chalcocite	78%		× 100
Black, gangue			
Fig. 13*e*.—White, pyrite	29%		Island and sea structure
Gray, chalcopyrite	71%		× 100
Black, gangue			

Plate VII

Fig. 13*f*.—White, chalcopyrite	35%		Island and sea structure
Gray, chalcocite	65%		× 100
Black, gangue			
Fig. 13*g*.—Dark gray, bornite	42%		Island and sea structure
Light gray, chalcocite	58%		× 140
Fig. 14*a*.—White, silver	6%		Vein structure
Gray, tetrahedrite	94%		× 100
Black, gangue			
Fig. 14*b*.—White, silver	10%		Vein structure
Gray, tetrahedrite	90%		× 100
Black, gangue			
Fig. 14*c*.—White, silver	17%		Vein structure
Gray, tetrahedrite	83%		× 100
Black, gangue			
Fig. 14*d*.—White, silver	24%		Vein structure
Gray, tetrahedrite and polybasite	76%		× 140

PLATE II

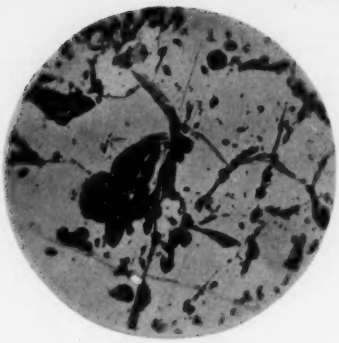

FIG. 10*a*
Granular Structure

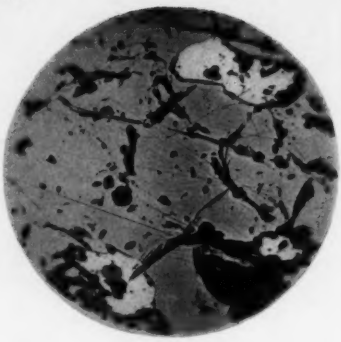

FIG. 10*b*
Granular Structure

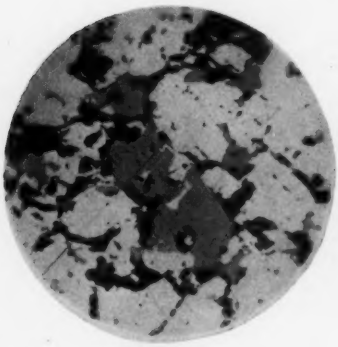

FIG. 10*c*
Granular Structure

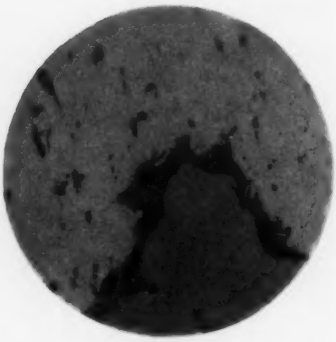

FIG. 10*d*
Granular Structure

FIG. 10*e*
Granular Structure

FIG. 10*f*
Granular Structure

PLATE III

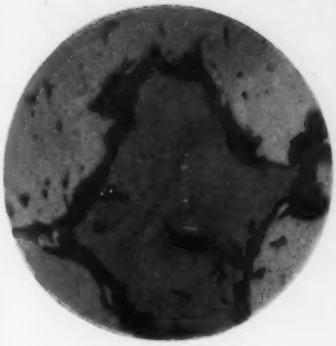

FIG. 10*g*
Granular Structure

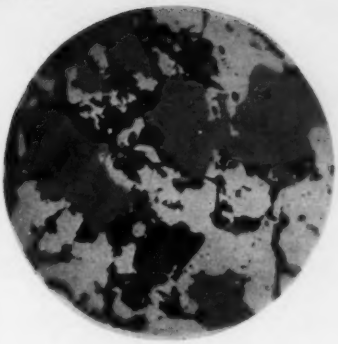

FIG. 10*h*
Granular Structure

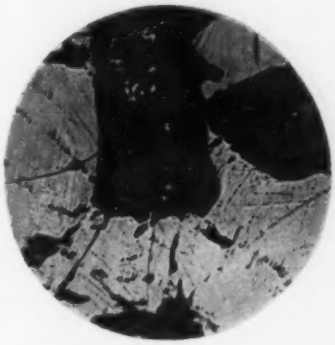

FIG. 10*i*
Granular Structure

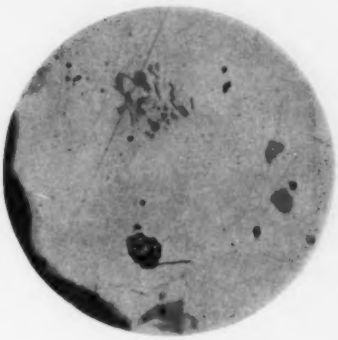

FIG. 11*a*
Graphic Structure

FIG. 11*b*
Graphic Structure

FIG. 11*c*
Graphic Structure

PLATE IV

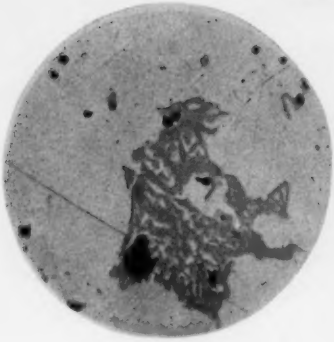

FIG. 11*d*
Graphic Structure

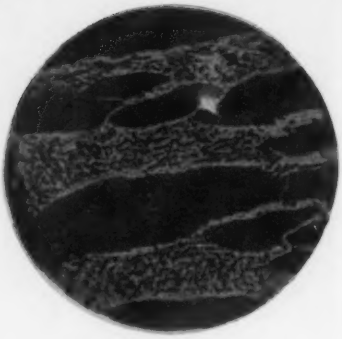

FIG. 11*e*
Graphic Structure

FIG. 11*f*
Graphic Structure

FIG. 11*g*
Graphic Structure

FIG. 11*h*
Graphic Structure

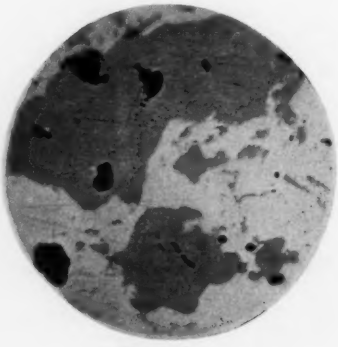

FIG. 11*i*
Graphic Structure

PLATE V

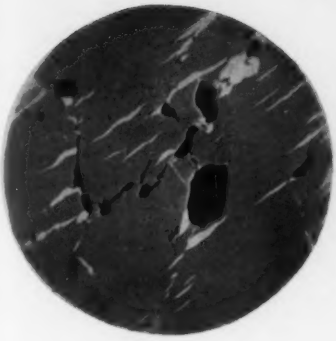

FIG. 12*a*
Grating Structure

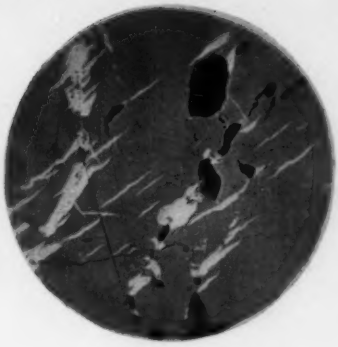

FIG. 12*b*
Grating Structure

FIG. 12*c*
Grating Structure

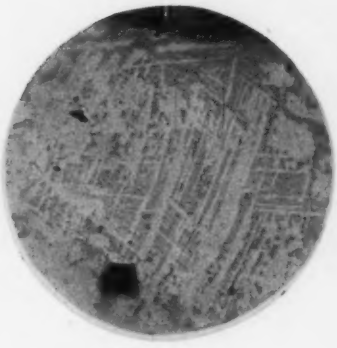

FIG. 12*d*
Grating Structure

FIG. 12*e*
Grating Structure

FIG. 12*f*
Grating Structure

PLATE VI

FIG. 12*g*
Grating Structure

FIG. 13*a*
Island and Sea Structure

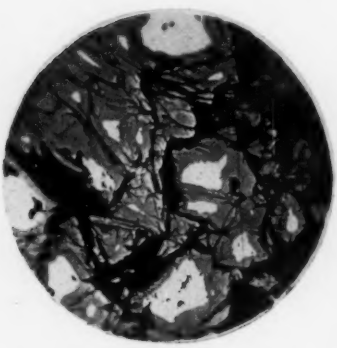

FIG. 13*b*
Island and Sea Structure

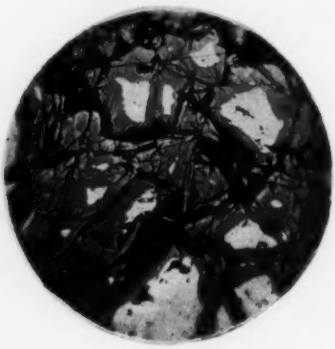

FIG. 13*c*
Island and Sea Structure

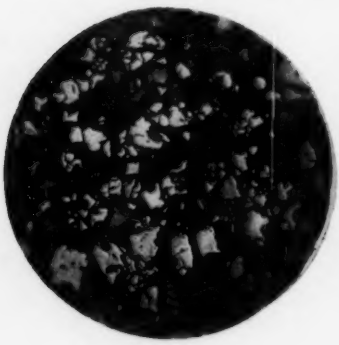

FIG. 13*d*
Island and Sea Structure

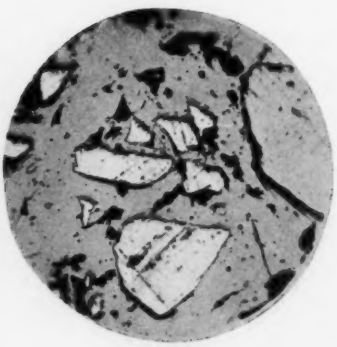

FIG. 13*e*
Island and Sea Structure

PLATE VII

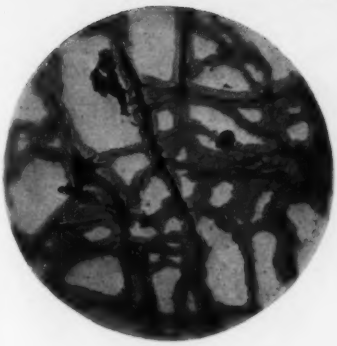

FIG. 13*f*
Island and Sea Structure

FIG. 13*g*
Island and Sea Structure

FIG. 14*a*
Vein Structure

FIG. 14*b*
Vein Structure

FIG. 14*c*
Vein Structure

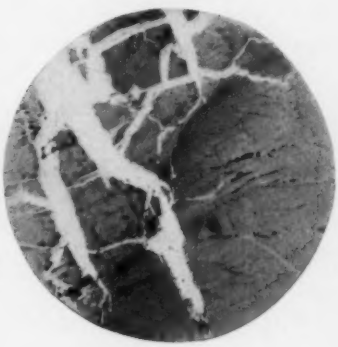

FIG. 14*d*
Vein Structure

PLATE VIII

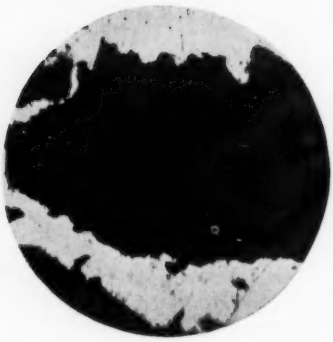

FIG. 14*e*
Vein Structure

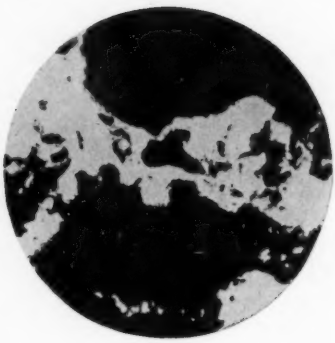

FIG. 14*f*
Vein Structure

FIG. 14*g*
Vein Structure

FIG. 14*h*
Vein Structure

FIG. 14*e*.—White, silver	28%	Vein structure
Black, gangue	72%	× 100
FIG. 14*f*.—White, silver	33%	Vein structure
Black, gangue	67%	× 100
FIG. 14*g*.—Light gray (l. rel.), silver	39%	Vein structure
Light gray (h. rel.), cobaltite	61%	× 140
FIG. 14*h*.—Light gray (l. rel.), silver	47%	Vein structure
Light gray (h. rel.), cobaltite	53%	× 140

LANTERN—LINEAL MEASUREMENTS

Adapting to this investigation the procedure as outlined by De Geer[1] for measuring clay varves in glacial deposits, an attempt was next made to enlarge the photomicrographs still further and so to increase the size of the measuring unit used that inaccuracies of measurement might be reduced to a minimum. This was done by projecting a lantern slide of a polished-section photomicrograph,

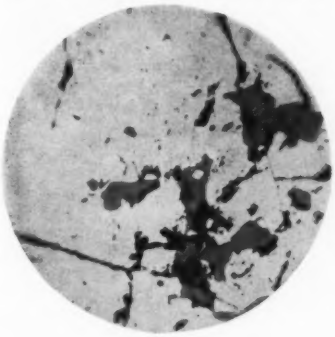

FIG. 15[2]
Light gray, pyrrhotite
Dark gray, sphalerite
Black, gangue
× 100

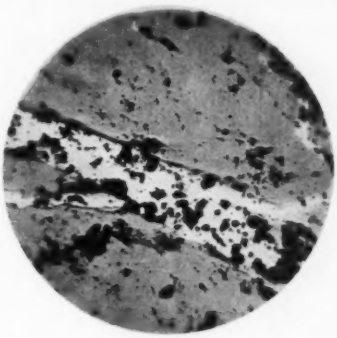

FIG. 16
Light gray, chalcocite and chalcopyrite
Dark gray, bornite
Black, gangue
× 100

with the square grid immediately behind or in front of it, on a blackboard or other convenient medium. Where the lantern is equipped with a slide-holder for slides of two different sizes, the grid may be conveniently made in one size, the lantern slide of the section in the other. If the lantern is equipped for but one size of slide, thin cover glasses may be substituted for the ordinary cover glass on the lantern slides both of the grid and of the section, so that both slides will fit into one holder. The lantern used for this purpose was one fitted with a powerful Mazda bulb, but a good steady arc-lamp with mechanical feed would serve equally well. Measurements were then made on the two sets of ten lines, using a meter stick divided into centimeters. Individual intercepts are readily marked off with chalk;

[1] G. De Geer, private communication.

[2] Proportions of minor constituents in: Figure 15, sphalerite, 8 per cent; Figure 16, chalcocite and chalcopyrite, 16 per cent. See page 203.

and if desired, colored chalk may be used to designate the intercepts of different minerals, which may then be measured at leisure with the ordinary room illumination. The latter device is recommended as saving the bulb or carbons during time of measurement, which varies from 20 to 35 minutes according to the character of the section.

Ten of these slides were determined by this modification of the lineal method, and for purposes of comparison were determined also lineally and areally directly on the slide.

TABLE II

No.	Mineral	Delesse	Lantern	Lineal	Areal	Maximum Difference between Delesse and Other Three Methods	Minimum Difference between Delesse and Other Three Methods
21	Silver	51.2	50.4	49.6	50.75	1.6	0.45
	Niccolite	14.9	16.0	14.0	12.50	2.4	0.9
	Galena	13.4	13.7	12.6	13.25	0.8	0.15
28	Chalcocite	30.5	32.0	33.9	31.5	3.4	1.0
31	Pyrrhotite	24.9	26.4	25.4	24.5	1.5	0.4
	Pentlandite	36.5	39.0	37.2	40.5	4.0	0.7
16	Galena	38.6	37.4	38.1	36.75	1.85	0.5
27	Silver	30.3	31.0	31.0	31.0	0.7	0.7
50	Franklinite	27.5	28.9	30.25	28.5	2.75	1.0
39	Galena	2.1	1.7	2.6	2.5	0.5	0.4
32	Pentlandite	23.3	22.8	23.1	21.75	1.55	0.2
15	Galena	37.6	38.1	37.6	34.5	3.1	0.0
38	Galena	46.8	47.9	47.7	46.25	1.1	0.55

DELESSE METHOD

As a further check on the figures obtained by these three methods, determinations were carried out on all ten slides by means of a variation of the Delesse method. Enlarged photographs of the lantern slides were made on heavy paper, increasing the magnification seven times. The individual areas occupied by each mineral were then cut out and the fragments of paper weighed. The relation between the weight of all the fragments and any set representing one mineral gave the percentage value of that mineral with regard to the whole.

Exactly the same areas in the slides were measured by all four methods, using the square grid throughout. Tables II and III show the results obtained and give some idea of the differences in the results obtained by the four methods.

COMPARISON OF METHODS

These figures seem to indicate that the three new methods compare very favorably with the Delesse method. If the last be taken as a standard, it will be seen that the divergence in the results obtained by any one of the new methods from those obtained by the Delesse method is remarkably small. In those sections showing the greatest difference—namely, Nos. 28 and 31—part of it at least may be attributed to the fact that differences of relief in the component minerals made the exact determination of mineral boundaries somewhat uncertain. Number 28 showed an association of chalcocite and

TABLE III

	Percentage			
	Difference between Delesse and Other Three Methods	Difference between Delesse and Lantern Method	Difference between Delesse and Lineal Method	Difference between Delesse and Areal Method
Average	1.14	1.04	1.03	1.35
Maximum	4.00	2.50	3.40	4.00
Minimum	0.00	0.30	0.00	0.15

hematite; No. 31, pentlandite and quartz. With more perfect methods of polishing[1] this factor could be eliminated to the benefit of the quantitative determinations.

A study of the figures in Table III would seem to show that, while all three of the new methods give reasonably accurate results in most cases, the two lineal methods by direct measurement on the slide and by measurement of the projected picture of the slide on the blackboard have a slight advantage over the direct areal method. As the measurements in the case of the lantern method were carried out with a square-cut meter stick and were observed in the somewhat indifferent illumination of the lantern, the writer feels that the results by this lantern method might be bettered by the use of a measuring rod which would fit close to the board and by marking off the mineral intersections with colored chalk and then substituting the normal room illumination for the rather feeble light provided by most lanterns. There seems very little reason to doubt that, other

[1] J. W. Vanderwilt, *Econ. Geol.*, Vol. XXIII, pp. 292–316.

things being equal, that method which employs the larger unit of measurement should be the more accurate, as already indicated. So that the divergence of results obtained by all four methods might be visualized more clearly, the following four-section-graphs (Figs. 17 and 18) have been devised, the sections representing from left to right the results obtained by the Delesse, the lantern, the direct lineal, and the areal methods. The last two columns of Figure 18 show sections Nos. 39 and 21 with the maximum and minimum proportions by volume, respectively, plotted on the basis of 100 per cent to show their relative divergence. From these two it would appear that the relative chance of error is greater where the proportion of the mineral constituent is smaller and does not increase as the proportion approaches the larger numbers, but rather decreases.

For purposes of comparison the results obtained by Johannsen and Stephenson[1] in their investigations on the Butte granite, using the three methods by calculation from chemical analysis, by calculation of weight percentage by the Rosiwal method, and by the use of heavy solutions have been plotted in the same way and are shown in Figure 19.

It will be noted that the difference in the results obtained by these three methods is appreciably greater than that shown in Figures 17 and 18, more especially in the case of the determinations carried out on the feldspars and on the combination of pyroxene and amphibole to which the name "pyribole" has been attached. If it be remembered that the methods by calculation from chemical analysis and by separation with heavy solutions, though admittedly subject to error, are still in use, it will be seen that the new methods, which are more accurate and are more easily carried out, deserve the attention of investigators in this special field of quantitative determination.

NEW FEATURES IN METHODS OF MEASUREMENT

What, then, are the new features of these three methods? Let it be admitted at the outset that all three are but adaptations of the original Rosiwal method and that nothing startlingly new is involved. Whatever novelty there may be lies in the fact that the areal estimation or the lineal measurement has been removed from

[1] *Op. cit.*

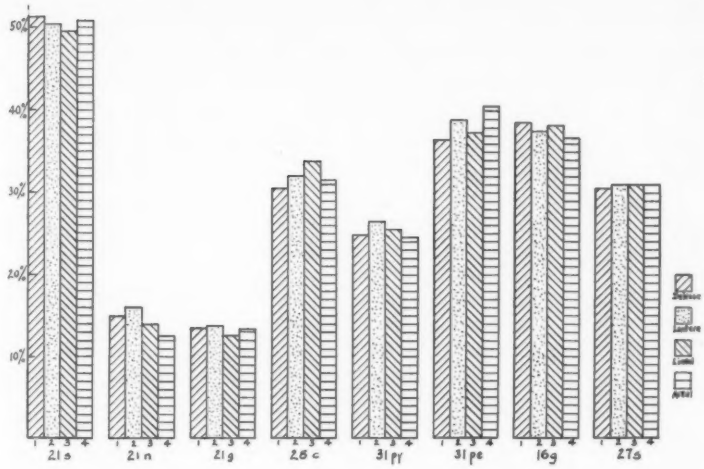
50%
40%
30%
20%
10%
21 s
21 n
21 g
26 c
31 pf
31 pe
16 g
27 s

FIG. 17

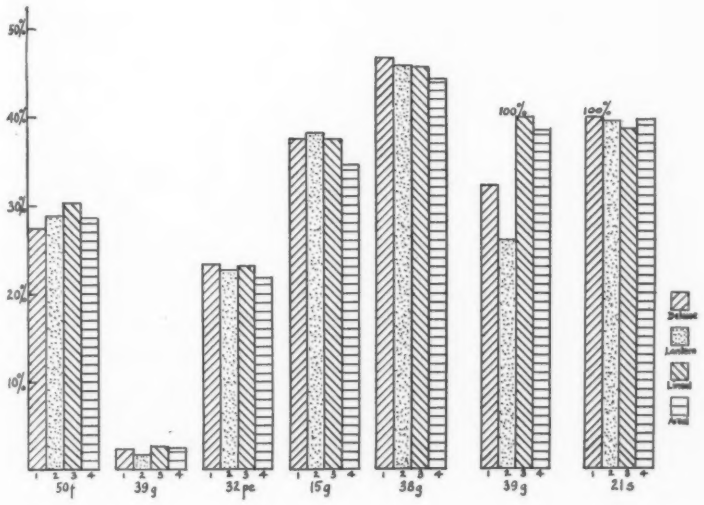
50%
40%
30%
20%
10%
100%
100%
50 f
39 g
32 pe
15 g
38 g
39 g
21 s

FIG. 18

the confined limits of the microscope and is carried out either on photomicrographs, ground-glass screens, lantern-slides, or on the projection of lantern-slides, via the lantern, on the blackboard. It is the writer's contention that increasing the magnification of the original picture and carrying out the measurements on a larger scale is bound to increase the accuracy of the determination and has,

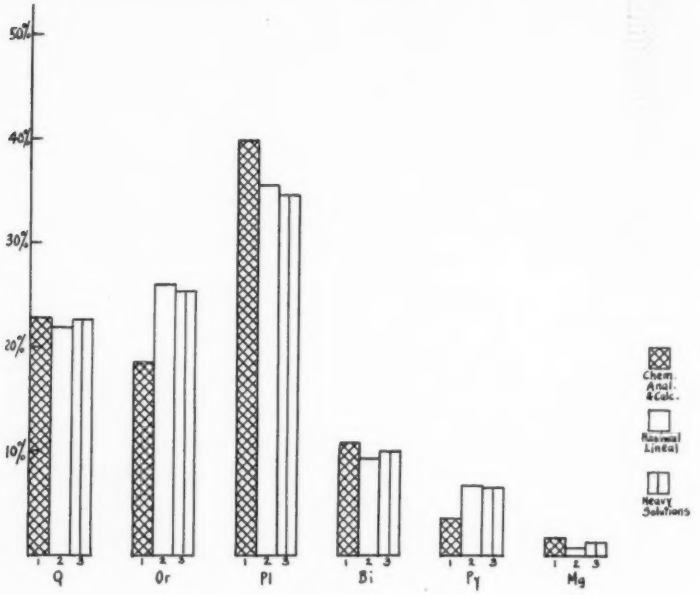

FIG. 19

besides, the added advantage of increasing the speed of operation. It is interesting to note in this connection that approximate determinations by comparison with standards may be accomplished within 1 minute, while measurement by the areal method consumes from 5 to 10 minutes, varying with the character of the section and also with the speed and precision of the operator. The direct-lineal and lantern methods require more time, but a determination can usually be carried out by either of these methods in from 20 to 30 minutes. The limitations imposed on these methods are but few and may be

outlined very briefly. The areal method, as before stated, is not well adapted to those sections where the individual constituents are very irregular in outline, widely scattered in distribution, or of a size smaller than the unit of measurement. Such difficulties may of course be overcome by increasing the magnification of the picture, but this involves an increased number of determinations on more sections, and for sections with these characteristics either one of the lineal methods is to be preferred. Where the individual mineral areas are smaller than the space between the measuring lines, the direct-lineal method gives but approximate results, which may, however, be bettered either by introducing a grid with closer spacing of the lines or by increasing the magnification. In such cases it would seem preferable to use the grid with the closer spacing in conjunction with the lantern method. In all three methods accurate determinations are rendered somewhat difficult where marked differences of relief make the exact fixing of mineral boundaries somewhat indefinite. This difficulty may, however, be overcome by more careful methods of polishing, which will largely eliminate such differences and produce something very close to an optically plane surface. All three methods involve the use of a photomicrographic apparatus but, as most investigators in the quantitative field have access to such equipment, this does not seem an obstacle of appreciable dimensions. Where such photomicrographic apparatus is not available, any one of three courses may be pursued. The sections may be sent away to the nearest apparatus of this sort, so that photomicrographs or lantern slides may be made of them, or an extra accessory may be obtained for the projecting lantern, which allows the picture of the polished rock or ore section to be projected directly on the blackboard so that the determination may be carried out without the preparation of a thin or polished section, and without any photomicrograph being called into requisition at all. In the case of polished ore sections, at least, the quantitative determination may be carried out, as already stated, directly on the back of the metallographic machine, using a special ground-glass plate equipped with a suitable cross-section arrangement.

On the other hand, the advantages of these methods seem to offset whatever limitations there may be to their use. They are simple of

operation, require no elaborate equipment other than the photomicrographic apparatus already mentioned, and are accomplished in a comparatively short space of time. As has been demonstrated, they produce results in the majority of cases accurate within 1 or 2 per cent and compare favorably in this respect with any methods used in the past. In reviewing the work of previous investigators in this field, it seemed that preference should be given to the planimeter method devised by Johannsen[1] and the recording micrometer devices of Shand[2] and Wentworth[3] as combining accuracy with reasonable speed of operation. It seemed to the writer, however, that, with the exception of these microscopists carrying out detailed quantitative investigations over long periods, most microscopic laboratories would not be equipped with such elaborate and costly accessories to the microscope. Moreover, both of these methods are carried out under the microscope and so are subject to the errors already mentioned. If, then, such common everyday things as the projecting lantern and the blackboard could be substituted, it was felt that the occasional investigator might be encouraged to adventure into this fascinating field.

FIELDS OF USEFULNESS FOR QUANTITATIVE MEASUREMENT

The directions of endeavor in which such methods may be employed are many, and it will suffice for the purposes of this paper to outline but a few of them. While all of the writer's experiments were accomplished on photomicrographs of polished sections, they could have been done with equal success on thin-sections of rocks, with the added advantage of greater homogeneity of material in most cases. Most petrographers will agree that there is still need of accurate quantitative work on the igneous rocks to place their classification on a proper basis. Given a quick accurate method, this task should not present insuperable difficulties and would be of inestimable benefit in reducing petrographic nomenclature to reasonable proportions. In the field of economic geology, particularly in that phase dealing with problems of metamorphism, the application of such methods would throw considerable light on the quantitative changes effected in the rocks and ores by contact action. In the study of the

[1] *Op. cit.* [2] *Op. cit.* [3] *Op. cit.*

opaque minerals in polished section, they can be employed for the solution of many problems. In sections containing a known and an unknown mineral, they can be used to great advantage in conjunction with chemical analysis to determine the unknown. They can likewise be used on thin or polished sections of fragmental material, such as mill products, to determine the proportion of metallics to non-metallics in tailings or concentrates, or the proportion of free silica to other constituents in a study of silicosis problems.

That such methods as these will entirely replace the time-honored procedure of chemical analysis and subsequent calculation into the proportion of minerals is scarcely to be expected. It is to be hoped, however, that, particularly where numerous photomicrographs are to be used in any case for purposes of illustration, the advantages of these methods in rapidity of operation and accuracy of results obtained will be realized, and that the older, more laborious, and less accurate methods may eventually be supplanted by these larger-scale operations.

SUMMARY

To recapitulate briefly the main points brought out in this paper:

1. It has been proved by many investigators that the Rosiwal method of quantitative determination is sound and capable of accuracy within 1 or 2 per cent.

2. It has been demonstrated by the preparation of synthetic mixtures of two minerals in the fragmental state in known proportions and their subsequent quantitative determination that the areal method of determination is very nearly as accurate as the lineal one advocated by Rosiwal, and is well adapted to most investigations.

3. The principle is enunciated that more accurate quantitative determinations may be carried out on the larger scale of photomicrographs or lantern slides than on fields of view under the microscope where counting or measuring is more difficult and induces eye-strain.

4. Good approximate quantitative determinations may be effected in a very short space of time for sections of both solid and fragmental material by comparing photomicrographs of any section with the quantitative standards established.

5. Lineal determinations may be carried out directly on the photomicrograh or on the projected picture of a lantern slide on the

blackboard with a slight advantage in accuracy for the latter variation.

6. Where it is impossible or undesirable to prepare photomicrographs, good results may be obtained on the ground-glass screen of the metallographic machine, equipped with a suitable cross-section device and with line-spacing to suit individual requirements.

7. The accuracy of these variations of the Rosiwal method has been tested against a variation of the Delesse method with surprisingly concordant results.

8. It is hoped that these newer methods may attract more investigators to this field and may prove less arduous and exacting, as to time and effort, than the older methods.

RECENT SANDS OF CALIFORNIA

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ABSTRACT

A study of about a score of recent sands collected from California deserts, beaches, and stream channels reveals the widespread occurrence of a feature that is interpreted as immaturity. Attention is called to the possible importance of this factor in the interpretation of certain Cretaceous and Tertiary sedimentary formations.

1. PETROLOGY OF A DESERT DUNE SAND

The Indio dune sand area covers several square miles in that part of the Colorado Desert which faces San Gorgonio Pass. This region has long been known as one of exceptionally violent winds. As early as 1855, W. P. Blake described the wind and its geological effects.[1] He found the granite and other crystalline rocks grooved and polished, with such hard minerals as garnet standing out in relief. According to Free, this account of Blake's introduced the conception of sand-blast action into geological thought.[2]

Further details as to eolian processes in the Indio region are given by Mendenhall:

> At certain seasons of the year strong winds blow toward the desert from San Gorgonio Pass and the mountains on either side of it. As these winds sweep down into the upper end of the desert they sift the sands from the alluvial material brought from the basins of the Whitewater, Mission Creek, Palm Canyon, and other streams, and carry them farther out into the desert basin. In this vicinity the effectiveness of the wind as a transporting agent is enormous. . . . . Since the Southern Pacific Railroad was built many . . . . proofs of this [wind] action may be seen (Plate VII, *A*). For example, the telegraph poles are worn away near the ground and have to be protected there by posts or rock piles. The more resistant knots or growth rings are brought into high relief by the etching of the softer parts. The fish plates and bolts of the railway tracks are eroded rapidly, and the tin cans strewn along the track are kept bright and polished by the driving sand and are quickly etched through, as by acid, and worn away.[3]

[1] W. P. Blake, "On the Grooving and Polishing of Hard Rocks and Minerals by Dry Sand," *Amer. Jour. Sci.*, Vol. LXX (1855), pp. 178–81.

[2] E. E. Free, "The Movement of Soil Material by the Wind," *U.S. Bureau Soils Bull. 68*.

[3] W. C. Mendenhall, "Groundwaters of the Indio Region, California," *U.S. Geol. Survey Water-Supply Paper 225* (1909), p. 26.

Equally striking examples of wind action may be seen on the windward slopes of the gravel-covered hills east of the Pass, near Garnet and Edom. The pebbles and boulders are so well worn that a whole hillside may glisten and sparkle in the sun. Dreikanter and similar forms, so rare in many deserts, may here be collected by hundreds; and many of the pebbles which lack the dreikanter shape show equally good evidence of wear by the sand blast (Fig. 11).

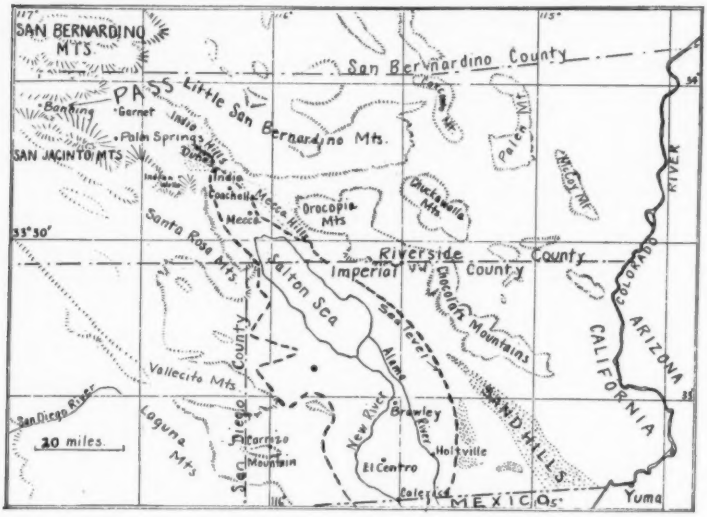

FIG. 1.—Index map of Colorado Desert

The Indio dunes, though not exceptionally large or extensive, have been noticed by all the geologists who have written about the region. The sketch map, Figure 1, is designed to show their relations to the more important features of the surrounding country: San Gorgonio Pass, the San Bernardino and San Jacinto Mountains, Salton Sea, the Sand Hills, and the surrounding desert ranges. Figure 2, sketched from part of a soil map of the Indio region,[1] shows in some detail the distribution of the dunes in a part of the area. Their average height is perhaps 15 feet. Most of them are partly

[1] J. Garnett Holmes, "Soil Survey of the Indio Area, California," *Field Operations of the Bureau of Soils, U.S. Dept. Agriculture* (1903), pp. 1249–62.

fixed by a scant growth of desert shrubs. The material composing the dunes, as noted by Mendenhall, is probably derived from Whitewater Wash and other ephemeral streams which flow from the crystalline rocks of the mountain ranges to the west. How far it may have been carried by the wind is uncertain, but the distance cannot be more than a few miles. Most of the grains are probably not more than a few tens of miles from their original home in the crystalline rocks. Some of the finer material, however, may perhaps

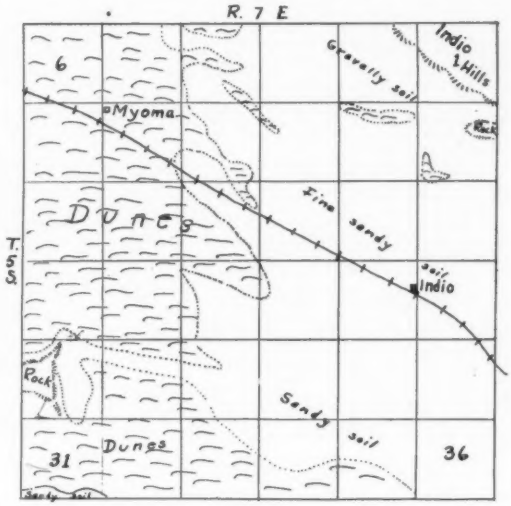

FIG. 2.—Sketch map showing soils, Indio Township

have been carried in from great distances— from the Mohave Desert, or the sandy coastal plain near Los Angeles.

A dune along the highway at Myoma Station about 4 miles northwest of Indio was largely cut away by a steam shovel early in 1926. The cliff face of the remaining portion is now partly obscured by talus, but its upper few feet, minutely etched by the wind, still gives a good view of the very uniform bedding (Fig. 3). Figure 4, showing the structure of a coastal dune partly cut away by wave action along the northeast side of Santa Rosa Island, illustrates ordinary dune bedding. The Indio dune, as now exposed, is so much

more regularly bedded as to be striking. It is probable, however, that the part exposed is not representative of the dune as a whole. The bedding is rendered conspicuous by the concentration of biotite into layers. Small flakes of bark also occur rarely in the same layers with the mica. The less micaceous layers are lighter in color, with a dominance of feldspar and quartz, but also with a conspicuous amount of mica distributed through them.

The sorting of the Indio sand is a variable feature, as illustrated in Figure 5, *A*, *B*, and *C*. In Figure 5, *A*, the sorting is poorer than

FIG. 3.—Bedding in a dune, Myoma Station, near Indio

is common in dune sands, or, indeed, in many water-laid sediments of similar grade. Some other beds of the same dune, on the other hand, differ little in sorting from more common dune sands. The problems suggested by the sorting of this sand can be more easily discussed in connection with the account, given later, of the sorting of a selected series of California sands of different types.

Some of the larger quartz and feldspar grains have the sharp edges and corners rounded, but spherical or subspherical grains have not been observed. Most of the finer material is sharply angular. The biotite flakes, many of which range from 1 to 2 mm. in diameter, show excellent rounding. Many of them are nearly circular disks, with battered edges and pitted surfaces. The contrast be-

tween the dune sands of Indio and those of the great Sand Hills east of Salton Sea is well shown in the microphotographs, Figures 6, 7,

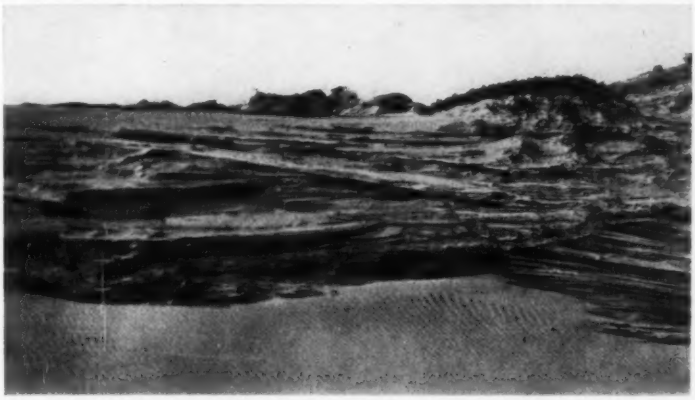

FIG. 4.—Bedding in a beach dune, Santa Rosa Island

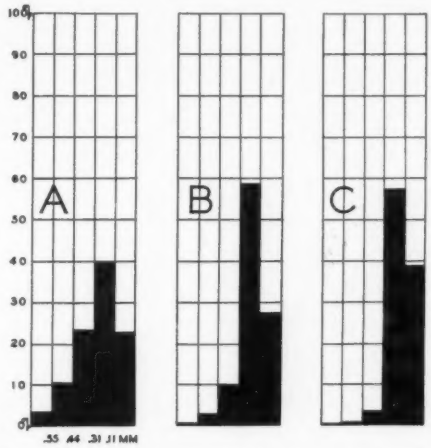

FIG. 5.—Distribution pyramids, Myoma dune samples

and 8. Small quartz grains of the latter are better rounded than any constituents of the Indio dunes except the easily worn mica flakes.

FIG. 6.—Myoma dune sand, from a coarse layer. The magnification in all microphotographs is approximately 20 diameters.

FIG. 7.—Myoma dune sand, average material

The mineralogy of the dune sand is very similar to that of the sand in the bed and banks of Whitewater Wash a few miles west of Indio, and not very different from that of the granitic soils scantily developed over the crystalline rocks of the surrounding mountains. In many slides prepared from the dune sand, mica appears to constitute about a third; its percentage by volume, however,

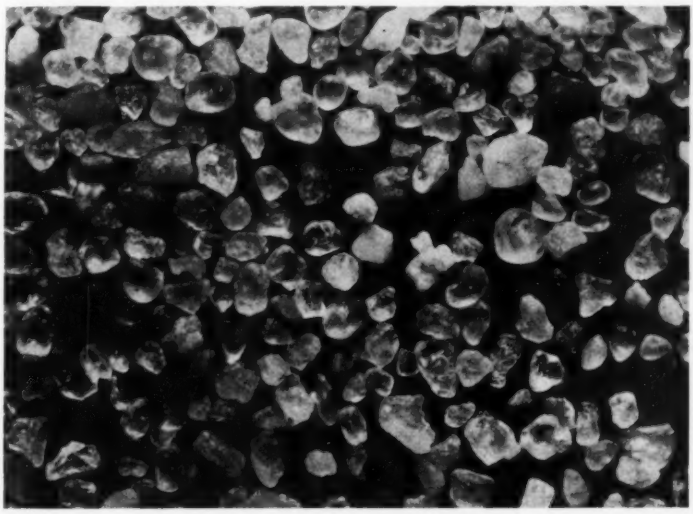

FIG. 8.—Sand Hills dune sand

must naturally be less than it appears to be in a slide. One conspicuously micaceous sample was studied by allowing a part of each size grade to settle in a tall graduate nearly filled with water. The mica settled out as a black layer above the other constituents. By this means, the proportion of mica in the sample was determined as about 18 per cent.

In the samples most carefully studied, feldspar is the most abundant constituent, and most of it is fresh. Orthoclase is more common than plagioclase. Many grains of the latter have refractive indices lower than those of quartz, but some of them have the indices of labradorite. Quartz is the next most abundant constituent. The rarer minerals include all those that might be expected to be

common in a sand derived from granitic rocks: green hornblende, muscovite, epidote, apatite, titanite, zircon, and garnet. Some of the grains, particularly those of apatite, are well rounded, possibly from wear.

RÉSUMÉ

The Indio dune sand has been transported and deposited by winds of far greater than average violence, and might therefore be expected to show in a high degree the characteristics commonly classed as eolian. On the other hand, it comes more directly than many dune sands from mountains of crystalline rocks which are probably subject chiefly to mechanical weathering. In bedding, the single dune examined appears to be much more regular than many dunes. In degree of rounding of grain, it falls far below the usual, or typical, eolian sand. Its rounded biotite grains are conspicuous, but perhaps common enough in other similarly micaceous dune sands. The sorting is variable; it is similar to that of the sands of Whitewater Wash, and is not very different from that of some coastal dunes, as will be shown later; it is greatly inferior to that of the Sand Hills east of Salton Sea, and to many beach and river sands. In mineralogy, the dune sand differs remarkably little from that of its parent-rocks in the San Jacinto and San Bernardino Mountains. It lacks almost entirely the mineralogical features—absence of mica, rarity of hornblende, dominance of quartz over feldspar—that are stated in many textbooks to be criteria for the recognition of desert dune sands. By analogy with certain stream deposits it could perhaps be classed as a "torrential" eolian sand.

2. THE SORTING OF CALIFORNIA SANDS

The Indio dune sand described in the foregoing differs noticeably from the type considered normal or typical. It is thus another in the long list of California sediments, ancient and modern, which fails to fit into the commonly recognized classes. So many of these are already known, especially from the older rocks, that it is becoming obviously dangerous to draw conclusions from a comparison of a peculiar California sediment with what is considered normal in other regions. For this reason, the interpretation of the Indio dune sand was postponed until a study could be made of a considerable

number of other recent sediments from known environments in California. These are all of sand grade, and include dune, river, and beach deposits. The results of the investigation are somewhat fragmentary, but sufficiently interesting in the present connection to warrant summarizing them here.

THE SAMPLES

1. *Indian Wells dune* (*Fig. 9, E*).—The sample studied is from a dune in the Indio area, $\frac{1}{4}$ mile west of the village of Indian Wells, and about 6 miles west of Indio; a short distance south of Whitewater Wash. This sand is micaceous, and similar in other respects to that from the Myoma dune, described in the foregoing.

2. *Edom dune* (*Fig. 9, D*).—Sample from dune in lee of a hill near Edom Station, 12 miles northwest of Indio; from finer part of the material. Fine gravels occur over a portion of the dune, with constituents 1–2 mm. in diameter. They are well rounded and polished. The opposite, or windward, slope of this hill is covered with dreikanter and wind-worn fragments of many sizes (Fig. 11).

3. *Sand Hills, between Holtville and Yuma* (*Fig. 9, F*).—The sample analyzed was collected by Mr. Walter Ward from the top of a dune estimated to be about 150 feet high, 29 miles east of Holtville. The sand of this area is discussed by Mendenhall[1] and by Brown.[2] The latter writes:

> The conclusion appears justified that the dune sand has been gathered from the west, and probably most of it originated by wave action when the old beach was formed. In fact it is very likely that the Sand Hills originated when the beach was forming and the supply of sand was being constantly augmented.

Much of this sand doubtless came ultimately from the Rocky Mountains, having been brought down to its delta by the Colorado River. Another part must have come from the desert mountains surrounding the ancestral Salton Sea (Blake's Lake Cahuila), and is thus similar in origin to the material built into the Indio dunes. The material is typical dune sand in sorting and rounding of grain (Fig. 8). Its mineralogy is noticeably less complex than that of the Indio sand. Mica is absent.

[1] W. C. Mendenhall, *op. cit.*

[2] J. S. Brown, "The Salton Sea Region, California," *U.S. Geol. Survey Water-Supply Paper 497* (1923), p. 29.

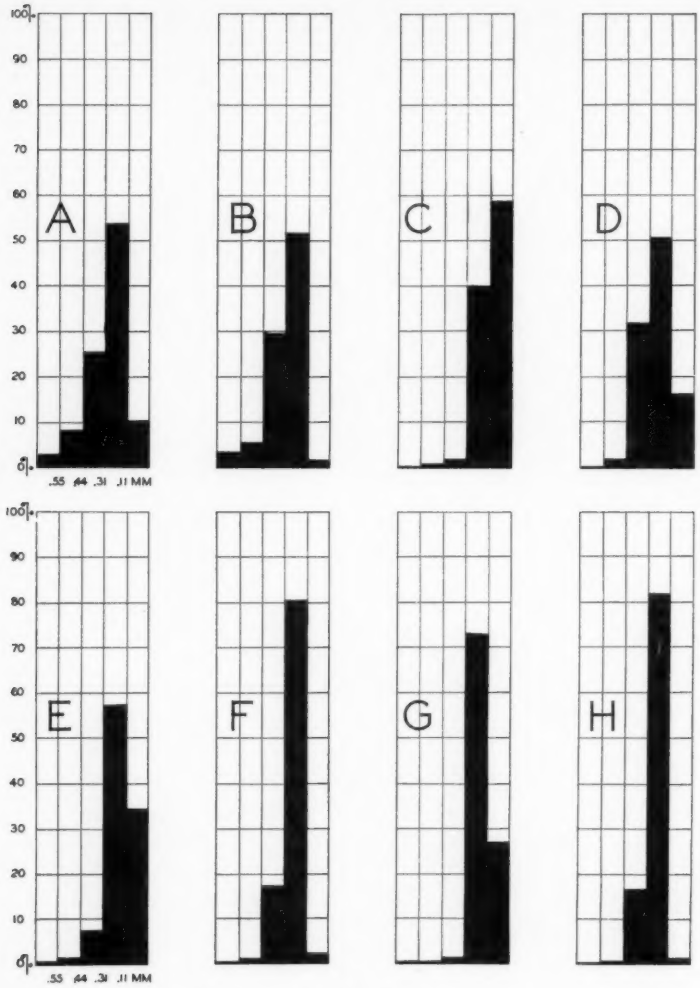

FIG. 9.—Distribution pyramids of recent sands:

A, Kern Lake dune;
B, Whitewater Wash;
C, Same;
D, Edom dune;
E, Indian Wells dune;
F, Sand Hills dune;
G, Owens Valley dune;
H, Santa Rosa Island dune.

4. *Owens Valley dune* (*Fig. 9, G*).—The sample studied was collected from a small dune near the outer margin of an alluvial fan in the edge of Owens Valley east of Big Pine. The dune sand is probably reworked from silt and fine sand on the floor of Owens Valley. A microscopic examination disclosed the fact that the material contains about 50 per cent of volcanic glass and pumice grains.

5. *Kern Lake dune* (*Fig. 9, A*).—The sample was collected from one of a small group of dunes fringing the southeast side of old Kern Lake, now dry, in the south end of the San Joaquin Valley. The dune sampled is situated about 1,000 feet south of the old beach line. The dune area is about a half-mile wide and a few miles long. The Inland Highway passes through it. The material of the sample is feldspathic and somewhat micaceous. It appears to have undergone some weathering since deposition.

6. *Santa Rosa Island beach dune* (*Fig. 9, H*).—Along the shore of Bechers Bay on the northeast side of Santa Rosa Island, dunes collect at the mouth of each small east-flowing stream, and all along the south shore of the bay. During the winter they are cut into and often removed entirely by the waves (Fig. 4). The sand appears to come chiefly from a great series of Miocene volcanic sandstones which outcrop over the adjacent part of the island. Zonally grown feldspar in euhedral crystals is abundant in the sandstone and conspicuous in the dune and beach sand. The appearance of this sand under the microscope is well shown in the photograph, Figure 12.

7. *Palisades del Rey dune* (*Fig. 10, J*).—The sample was collected from the top of one of the coastal dunes between Santa Monica and Redondo, California. The material is reworked from beach sand, which is here very coarse. The relation of the dune sand to sand from the adjacent beach is shown graphically in the curves, Figure 13. The grains are angular, and many of them consist of feldspar.

8. *Salinas River dune* (*Fig. 10, E*).—The sample was collected from one of a small group of dunes in the edge of the wide, sandy channel of the Salinas River near San Lucas, Monterey County. These dunes were made from river sand by the famous wind which sweeps up the Salinas Valley nearly every summer afternoon.[1] The

[1] R. D. Reed, "Wind and Soil in the Gabilan Mesa," *Jour. Geol.*, Vol. XXXV (1927), p. 87.

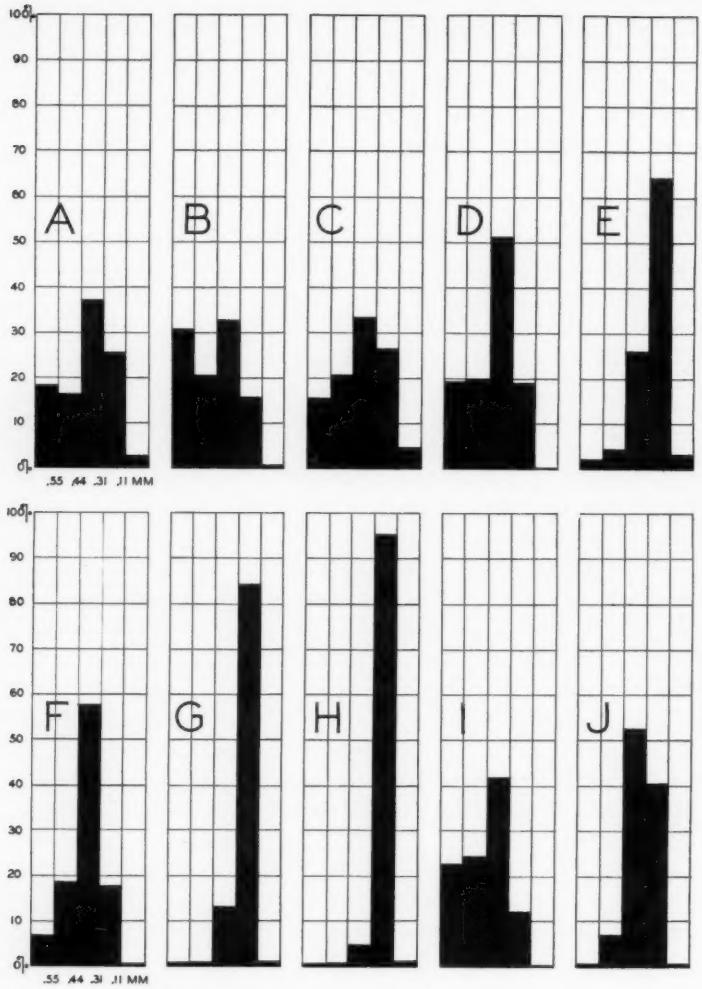

FIG. 10.—Distribution pyramids of recent sands:

A, San Antonio River;
B, San Gabriel River;
C, Castac sand;
D, Salinas River;
E, Salinas River dune;
F, Santa Cruz Island beach;
G, Santa Rosa Island beach;
H, Long Beach, beach;
I, Palisades del Rey, beach;
J, Palisades del Rey, dune.

relation of the dune sand to the river sand from which it was derived is illustrated in Figure 10. Both sands contain moderate amounts of mica.

9. *Palisades del Rey beach* (*Fig. 10, I*).—This beach is exposed to the full force of waves from the west, and the feldspathic sand is

FIG. 11.—Windworn pebbles from hillside, west of Indio. The largest fragment is 10 inches long.

appropriately coarse. It is derived from the old rocks (slates and granites) of the Santa Monica Mountains, and from younger rocks probably also derived from them.

10. *Long Beach beach* (*Fig. 10, H*).—The sample came from the upper part of the beach about a half-mile east of the amusement center. Wave action here is less strong than at Palisades del Rey, and the material supplied to the waves is largely fine sand and silt

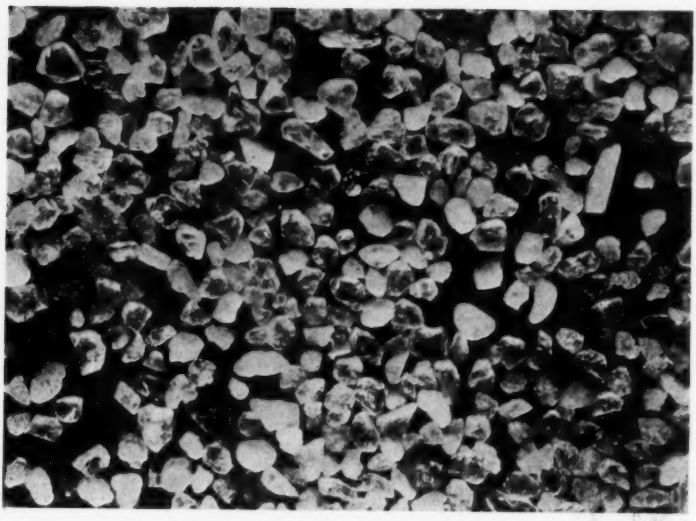

FIG. 12.—Dune Sand, Santa Rosa Island

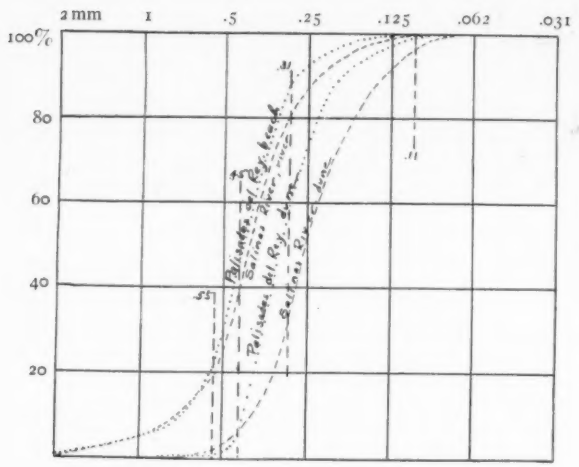

FIG. 13.—Cumulative curves of four California sands

from Tertiary and recent deposits of the Los Angeles Basin. The adjacent sea cliff is composed of fine sand, silt, and mud.

11. *Santa Rosa Island beach* (*Fig. 10, G*).—The sample studied comes from Bechers Bay, not far from where the dune sand, Number 6, was collected. The beach sand in this locality is very largely reworked dune sand.

12. *Santa Cruz Island beach* (*Fig. 10, I*).—The material comes from a narrow strip of gravelly beach at the mouth of a small canyon

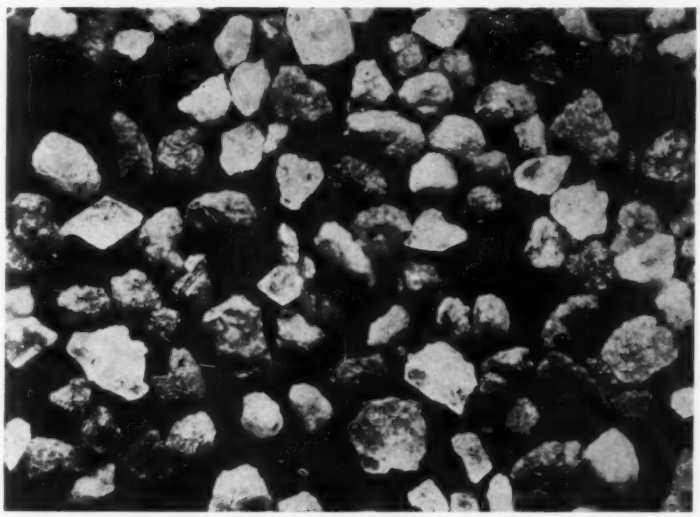

FIG. 14.—Beach sand from volcanic rocks, Santa Cruz Island

draining from the high, central ridge and emptying along the north side of the island. The coarser beach material is chiefly gray and reddish porphyry and other volcanic rocks, and the sand is dark gray in color. It is derived almost entirely from the Miocene volcanic rocks that make up this part of the island. A microphotograph of this sand is reproduced as Figure 14. It makes evident the high proportion of volcanic rocks among the sand grains.

13. *Castac sand* (*Fig. 10, C*), *deposited by the flood accompanying the breaking of St. Francis dam, in the spring of 1928.*—The sample

studied was collected from the site of the Castac Service Station, which was swept away by the flood. The flood plain of Santa Clara River is here covered with sand to a depth of 2 or 3 feet and a width of ½ mile. The site of the demolished filling station is about a quarter mile from the river bank. The sample is average material. It consists of angular, poorly sorted grains, with much feldspar and many grains of biotite and hornblende (Fig. 15).

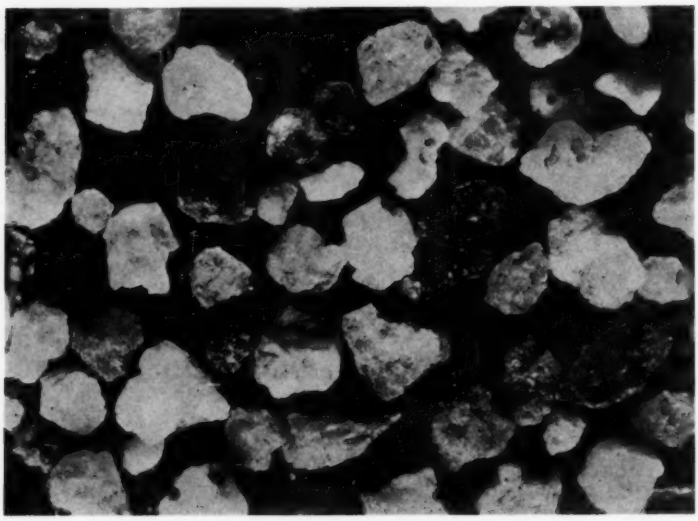

FIG. 15.—Flood-deposited sand from Castac

14. *Whitewater Wash, bottom of channel, near Indian Wells.*—This sample comes from the lower part of the Wash, where it crosses the Indio dune area. The sand is rather fine (Fig. 9, *B*), especially when compared with that which is common a little farther upstream. The material consists of angular grains, with much mica and hornblende, much feldspar, and some small fragments of crystalline rock. It is similar to the Myoma dune sand, but has rather less mica.

15. *Whitewater Wash, bank of channel, same locality.*—A finer sand (Fig. 9, *C*), similar in mineralogical features to that last described.

16. *San Antonio River* (*Fig. 10, A*).—From a bar in the channel of the river not far from the old San Antonio Mission in Monterey County. The material is derived from chiefly igneous and metamorphic rocks of the Santa Lucia Mountains. The grains are angular, poorly sorted, and mineralogically varied. In general appearance as well as in the sorting curves it yields, this sand is remarkably similar to the Castac material, No. 13.

17. *San Gabriel River* (*Fig. 10, B*).—The sample was collected near Artesia, in the Los Angeles Basin, from a part of the river bed which has been straightened and diked so that the channel is 100 feet wide. All the bottom material is coarse sand or fine gravel, and shows clear evidence of its derivation from the crystalline rocks of the San Gabriel Mountains.

18. *Salinas River* (*Fig. 10, D*).—From the flood plain of the river not far from the sand dunes which furnished sample No. 8.

In addition to those listed, a considerable number of other sands were screened and otherwise studied, but are omitted here because they failed to show any features not sufficiently well illustrated by those already described.

METHODS OF STUDY

The sands collected were all examined carefully in the field, and have been studied more or less thoroughly under the microscope. In all of them except the Sand Hills dune sand, the grains are nearly all angular. All are high in feldspar; they vary in other mineralogical respects, as outlined in the foregoing. The sorting seemed to be the characteristic easiest to determine quantitatively and to illustrate graphically. This feature was therefore investigated more elaborately than the others, and the results will be presented in the pages that follow.

The screens used in the investigation were specially made of brass, and are 4 inches in diameter. The mesh-openings ordered were as follows: 1 mm., 0.5 mm., 0.25 mm., and 0.1 mm. The actual openings vary considerably from the specifications, being as follows: 0.56 mm., 0.44 mm., 0.31 mm., and 0.11 mm. The range of openings is thus little more than half that which was desired. By good fortune, all the sediments studied have their most abundant

size grade well within these limits. Screens from another set were used to determine the percentage of each sand coarser than 2 and 1 mm., and the largest and smallest grains in most samples were determined microscopically. The quality of the screens used is good, only one—that with 0.31 mm. meshes—having some holes that are noticeably rectangular instead of square. It caused some difficulty in use, since longer shaking is required with it than with the others; besides, there is no good way to tell when, if ever, the separation secured is comparable to that given by the other screens.

In the beginning of the investigation, the screens were shaken in a mechanical shaker. Although theoretically excellent, the method developed so many difficulties and uncertainties that it was soon abandoned. Some of these arose from imperfections in the shaker available, but others would seem likely to apply with any machine. Shaking by hand, often considered hopelessly inefficient, is time-consuming and wearisome, to be sure, but the results obtainable seemed sufficiently accurate and dependable for the purposes of the present study. After a sample had been shaken a while, the coarsest screen was removed and shaken vigorously over a sheet of clean paper. If the quantity of sand passing the screen was extremely small, the contents were emptied on the paper and the screen, still inverted, was vigorously jarred and shaken. It was then righted, refilled with the same material, and shaken over the paper again. This method was used with each screen in turn. It separates a considerable amount of fine material, which, caught in some way, would otherwise fail to pass the given screen.

In most cases 50 grams of sand were used. The loss may with care be kept down to a very few tenths of a gram. The separate fractions were weighed on balances to the nearest tenth of a gram. The weights were calculated as percentages, and the results plotted and studied in different ways.

METHODS OF PLOTTING RESULTS

Ordinary distribution pyramids (Figs. 9 and 10) give an excellent picture of the proportions of sand belonging to each size grade, and are readily compared with one another if the same set of screens has been used throughout. The shape of the curve depends very

directly on the ratios of mesh-openings in the screens, however, as well as on the sorting of the material. If comparisons are to be made of sediments analyzed with sets of screens differing in mesh, therefore, the results must first be recalculated.

In order to bring to more general attention an excellent method of recalculation, as well as to exhibit the interesting relations of two pairs of samples, Figure 13 is introduced. It gives the cumulative-percentage curves yielded by two dune sands and the source

TABLE OF ANALYSES

	† mm.	‡ mm.	2 mm.	1 mm.	0.56 mm.	0.44 mm.	0.31 mm.	0.11 mm.	‡0.11 mm.
Myoma feldspathic, dune	2	0.05	*	*	3.6	10.6	23.2	39.8	22.8
Same, micaceous bed	2	.05	*	*	.6	3.0	10.0	58.8	27.6
Same, "average"	1.25	.04	—	*	.2	.4	3.3	57.3	38.8
San Antonio River	3	.01	0.5	9.0	9.1	16.6	37.0	25.2	2.6
San Gabriel River	2.5	.01	1.0	7.8	22.0	20.2	32.6	15.6	.4
Castac "flood"	2.5	.01	—	.5	14.9	20.4	33.2	26.4	4.6
Salinas River	?	?	.8	4.4	14.4	20.0	51.2	9.2	*
Salinas River, dune	?	?	—	*	2.2	4.4	26.0	64.2	3.2
Santa Cruz, beach	2	.05	*	.4	6.2	18.4	57.2	17.4	.4
Santa Rosa, beach	1	.01	—	.1	.6	.4	13.1	84.6	1.2
Long Beach, beach	.7	.05	—	‡	.05	.15	4.4	94.6	.8
Pal. d. Rey, beach	2.5	.08	*	2.3	20.2	24.0	41.4	12.0	.1
Same, dune	1.0	.10	—	*	.6	6.6	52.2	40.0	.4
Kern Lake, dune	1.5	.03	—	.2	2.4	8.1	25.4	53.7	10.2
Whitewater Wash	2	?	*	.8	5.4	8.6	35.0	40.8	9.4
Same	1.5	.01	—	*	.2	.4	1.2	39.8	58.4
Edom, dune	1.5	.05	—	*	*	1.8	31.8	50.4	16.0
Indian Wells, dune	1	.03	—	*	.4	1.0	7.0	57.4	34.2
Sand Hills, dune	.8	.05	—	‡	*	.2	17.6	80.4	1.8
Owens Valley, dune	1	.05	—	*	0.2	0.2	0.8	72.5	26.4

* trace; — absent; † diameter of largest grains; ‡ diameter of smallest grains.

material from which each was derived. In each case, the curve of the dune sand lies farther to the right—that is, toward the side reserved for the finer size grades—than the curve for the source material. The vertical dashed lines represent the mesh-openings of the screens in the set chiefly used. Unbroken vertical lines represent the openings of a standard set of screens. The course of the curves beyond the position of the coarsest and finest screen of the set used was determined, as suggested in the foregoing, by the use of the microscope, and of additional screens borrowed from another set.

From this diagram it is possible to read off directly the amount

of each sand that is coarser than each of the standard screens. A series of simple subtractions then gives the amount of material that should be caught by each screen of the standard set, and the results may readily be plotted in distribution pyramids similar in shape to those of Figures 9 and 10. Further details concerning these interesting curves and their uses may be found in the publications cited,[1] especially in Wentworth's valuable article.

DISCUSSION OF RESULTS

Dune sands.—The coarsest, most poorly sorted dune sand of all is a sample from a feldspathic bed of the Myoma (Indio) dune. It has 23 per cent in screen 3 (0.31 mm. mesh), and less than 40 per cent (the maximum) in screen 4. The Indian Wells dune sand, from the same general area, has sorting similar to that of the finest Myoma sample. The Edom and Kern Lake sands resemble each other, having 32 per cent and 25 per cent, respectively, in screen 3, but more than 50 per cent in screen 4. Neither of the latter samples has as much material in the two coarsest grades as the feldspathic Myoma sample. In contrast to all these, the Sand Hills and Santa Rosa Island dune sands are typically eolian in sorting, as in other respects; and the Owens Valley sand, in spite of its peculiar mineralogy, is similar. The Salinas River dune sand is interesting chiefly for its relation to the river sand from which it was derived. It has a maximum of 64 per cent in screen 4, and 26 per cent in screen 3. It is thus better sorted than the river sand which gave rise to it, but much less well sorted than many eolian sands. The Palisades del Rey dune sand, collected from a beach dune on an exposed shore, differs from all the others in having its maximum (52 per cent) in screen 3, with only 40 per cent in screen 4. In the two coarsest grades, however, it has less material than the feldspathic Myoma sample.

River sands.—Four of the river sands differ from dune sand in having from 15 to 20 per cent in each of the two coarsest screens. All four, furthermore, have their maxima in screen 3, whereas all but one of the dune sands have it in screen 4. It should be noted,

[1] A. Holmes, "Petrographic Methods and Calculations" (London, 1921), p. 215; C. L. Dake, "The St. Peter Sandstone," *Univ. Missouri School of Mines and Met. Bull.*, Vol. VI (1921), p. 157; Chester K. Wentworth, "Methods of Mechanical Analysis of Sediments," *University of Iowa Studies*, Vol. XI, No. 11 (1926), p. 49.

however, that all the streams represented by these four samples, except the Salinas River, are short, with steep gradients; and that even the Salinas River sample comes from near the middle rather than from the lower part of its course. Furthermore, if the diagram for it is compared with that for the sample from its tributary, the San Antonio River, a decided improvement in sorting is noticeable. The Whitewater Wash samples come from its lower, sluggish portion, and are noticeably finer and better sorted than the rest. One of them would pass for a moderately well-sorted dune sand, and the other differs from it chiefly in having its maximum in the finest grade.

Beach sands.—The beach sands differ much among themselves. That from Palisades del Rey, on the one hand, recalls the poor sorting of the Castac flood-deposited sand, and that from Long Beach, on the other, is the best sorted sand in the whole collection. The Santa Rosa Island beach and dune sands are practically indistinguishable, and the volcanic sand from Santa Cruz Island is about as well sorted as the Salinas River sand.

RÉSUMÉ

A consideration of all the diagrams shows clearly the difficulty of distinguishing sands of different origins by a study of their sorting. Whether or not the average dune sand differs from the average beach or river sand, it is certain that any given beach or river sand may more closely resemble typical eolian sand than any one of several actual eolian sands. The samples analyzed seem, in fact, to have more exceptions to, than examples of, any general rules that might be formulated. This condition is most readily accounted for on the assumption that the different sands owe their distinguishing features, not so much to the agent that sorted and deposited them, as to some other factor. The complex mineralogy of most of them suggests the same conclusion.

3. CONCLUSIONS

The results of these investigations lead to the conclusion that the Indio dune sand, striking and uncommon as it is, differs only in degree from many, if not most, California sands, eolian and other.

The majority of them have a characteristic that seems best described as *immaturity*. In other words, they would have required a large additional amount of wear and sorting during transportation to reach the stage considered normal in many regions.

The probability that eolian sands of this character exist has been explicitly recognized by many geologists, Dake[1] and Cressey[2] among them, and examples have been described by several observers. Johannes Walther[3] mentions several micaceous dune sands, for example, and discusses their occurrence as follows: "Near the crumbling mountains we still find all the constituents together. Soon, however, the wind sifts this *embryonic* sand and at last leaves an almost pure quartz sand which stretches out from the mountains in long bands, and wanders onward as dunes."

In an excellent recent discussion of wind action, based on extensive investigations of eolian sands in the central Sahara Desert, Jacques Bourcart[4] reaches similar conclusions, and states them in a form perhaps even more directly applicable to California conditions.

The conclusion[5] seems reasonable, then, that the Indio sand is simply an illustration of a principle that operates everywhere, and may become important in regions of a certain type. In California at present, for example, conditions of weathering and kinds of sand-yielding rocks are highly varied, and the average distance of transportation of sediments is small. Under such circumstances there is no apparent reason why many sands should not be finally deposited while still owing their most distinctive features to the kind of material available to the transporting agent, rather than to the effect of the agent itself.

[1] C. L. Dake, *op. cit.*, pp. 145 ff.

[2] G. B. Cressey, "The Indiana Sand Dunes and Shore Lines of the Lake Michigan Basin," *Geog. Soc. Chicago Bull., No. 8*, p. 28.

[3] J. Walther, *Das Gesetz der Wüstenbildung* (4th ed.; Berlin, 1924), pp. 265, 267–68.

[4] J. Bourcart, "L'Action de vent à la surface de la terre," *Revue de Geog. Phys. et de Geol. Dynamique*, Vol. I, Fasc. 1 et 3 (1928), pp. 249–50.

[5] This conclusion is in harmony with that of Mr. G. E. Anderson (this *Journal*, Vol. XXXIV, pp. 144–58), who found that the rounding of sand grains is a much slower process than had been believed earlier. On the relative importance of wear by wind and water, discussed by Mr. Anderson, the present study throws no light.

This conclusion is of possible geological importance because there is reason to believe that present physiographic conditions in California do not differ greatly from those that have existed during much of Mesozoic and Cenozoic time. Such studies as the present one may accordingly contribute data of importance in the interpretation of some of the puzzling features of many Cretaceous and Tertiary formations.

ACKNOWLEDGMENTS

The writer is under obligations to several friends for assistance in collecting samples and in discussing their peculiarities. He is especially indebted to Dr. M. I. Goldman, not only for assistance in the interpretation of the Indio dune sand, but also for the loan of an important publication not otherwise available.

THE HILLSBORO SANDSTONE OF OHIO

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ABSTRACT

A restudy of the Hillsboro sandstone of Highland County has shown that those exposures formerly interpreted as sandstone layers interbedded in the Greenfield and the Niagaran dolomites are really masses of sandstone completely enclosed in the dolomites, not more than 25 feet below the Silurian-Devonian disconformity, which here cuts across the Greenfield and Niagaran dolomites. These masses were formed from sand washed down into cavities that existed beneath this erosion surface. The remaining exposures of the Hillsboro are of bedded sandstone resting on either the Greenfield or the Niagaran at the horizon of the disconformity.

By this interpretation the Hillsboro comes in a hiatus which extends from the Greenfield dolomite of Upper Silurian (Cayugan) age to the Ohio shale of Upper Devonian age. It is in the same hiatus as the Sylvania sandstone of early Devonian age of northwestern Ohio, but this hiatus in Highland County extends farther downward and farther upward.

EARLIER STUDIES BY ORTON AND PROSSER

In 1871 Dr. Edward Orton named a sandstone, exposed in Highland County in southwestern Ohio, the Hillsboro sandstone.[1] He assigned to it a thickness of 30 feet, and described it as resting upon the Niagara limestone and overlain by the Helderberg (Monroe) or by the Ohio shale. In one section, however, he described it as interstratified in the upper part of the Niagara. He called it the highest member of the Niagara series and interpreted the sandstone as marking the beginning of the change from the limestone and shaly limestone of the Ordovician and Silurian systems below to the sandstone and shale of the Devonian and Carboniferous systems above. Brief statements were made concerning the Hillsboro sandstone by Dr. Orton in several later reports of the Geological Survey of Ohio, but no new data were given. In one of these reports he stated that "its reference to the Niagara series in its entirety is not beyond question.[2]

In 1916 Dr. Charles S. Prosser published an article entitled "The Stratigraphic Position of the Hillsboro Sandstone,"[3] in which he reviewed the work of Dr. Orton and gave sections of several of the ex-

[1] *Geol. Survey Ohio, Rept. of Progress in 1870*, pp. 283–85, 306–7.

[2] *Geol. Survey Ohio*, Vol. VI (1888), p. 14.

[3] *Amer. Jour. of Sci.*, Vol. XLI (1916), pp. 435–48.

posures of the Hillsboro sandstone and associated formations in Highland County. All the zones of Hillsboro sandstone recorded in Prosser's sections are relatively thin, being from 2 to 4 feet thick. He recorded Cedarville (Niagaran) dolomite below sandstone in some sections and Monroe (Greenfield) dolomite above sandstone in other sections, but most of the units of dolomite that touch the sandstone he left undesignated as to formation. In one section from Quaker Hill[1] he recorded two horizons of sandstone with Cedarville dolomite below the lower sandstone and Monroe dolomite above the higher sandstone, but did not designate by formation the dolomite between the two sandstone horizons.

Dr. Prosser did not definitely state his conclusions as to the stratigraphic position of the Hillsboro sandstone or give an interpretation of its origin, but on the basis of his sections one might conclude that the sandstone is interstratified in both the Cedarville and the Monroe divisions. Dr. Orton had definitely stated that in the Grady Hill section "the sandstone is interstratified with the Pentamerus and Megalomus beds" (Cedarville).[2] The only unit of the Monroe division present in Highland County is the basal member, the Greenfield dolomite, and subsequent reference to this will be by the name Greenfield. For the Middle Silurian dolomite below, the Cedarville of Prosser's article, the series name Niagaran will be used.

A NEW INTERPRETATION OF THE ORIGIN OF THE HILLSBORO SANDSTONE

The Hillsboro sandstone is a fine-grained, well-assorted, friable, quartz sandstone, the grains being very well rounded. There are no grains of quartz in any of the associated dolomite, either Niagaran or Greenfield. This purity of small masses of sandstone bedded in the dolomites and the complete absence of grains of quartz in the associated dolomites raises the question whether the sandstone is actually interstratified with the dolomite, that is, whether the sandstone and the surrounding dolomite are essentially contemporaneous in age.

There are relatively few exposures of the Hillsboro sandstone, and these are, in general, poor exposures chiefly along shallow, road-

[1] *Amer. Jour. Sci.*, Vol. XLI (1916), pp. 437–38.

[2] *Geol. Survey Ohio, Rept. of Progress in 1870*, p. 283.

side gutters. The authors of this article have restudied all the exposures recorded by Orton and by Prosser that could be located, and have found a few additional exposures. The various poor exposures were dug out with pick and shovel so as to show the contacts better than they had been shown before. Our chief emphasis has been placed upon the relation of the sandstone to the associated dolomites, in an attempt to determine the true stratigraphic position of the sandstone and its exact geologic age.

FIG. 1.—Diagrammatic cross-section, showing the relations of the sheet type *A*, *A'* and the cavity-filling type *B*, *B'* of Hillsboro sandstone to the Niagaran and Greenfield dolomites at the time of deposition of the sandstone. The present surface is shown by the heavy broken line.

As a result of this study, we now recognize two classes of sandstone rock-bodies as follows:

1. Bedded sandstone, resting upon either Niagaran or Greenfield and occupying commonly the hilltops of the present topography, as shown by *A* and *A'* in Figure 1. This class includes the larger areas of outcrop measured in acres or fractions of a square mile. These exposures are remnants of a probably discontinuous deposit of sand laid down on a post-Greenfield erosion surface which truncated both the Greenfield and the Niagaran dolomites. It was later buried by the Ohio shale, but over most of Highland County the Ohio shale has been eroded away, as well as much of the sandstone, but leaving a few remnants of the sandstone capping certain hilltops.

2. The second class includes all those sandstone bodies that are exposed on hill slopes with either Niagaran or Greenfield outcropping both down the slope and up the slope, as shown by *B* and *B'* in Figure 1. These masses were interpreted by Orton and by Prosser as beds interstratified with, and of contemporaneous age with, the dolomites. They are here interpreted as masses of sandstone completely enclosed in either the Niagaran or the Greenfield. The contacts of the sand-

stone with the dolomite are in all cases sharp without any mixing of the two materials, the lateral contacts being just as definite as the upper and lower contacts. All the sandstone masses belonging to this class are small, the largest known case being about 25 feet across.

These sandstone masses are interpreted as fillings of cavities in either the Niagaran or the Greenfield dolomites by sand washed down along passages or joint cracks from the post-Greenfield erosion

FIG. 2.—Map of Highland County, showing the location of the three regions with exposures of Hillsboro sandstone: (1) Lilley Hill near Hillsboro; (2) Quaker Hill near Samantha; (3) Rhoads Corner northwest of Sinking Spring.

surface upon which the sheet deposit of the Hillsboro sandstone was accumulating. They are all within from 20 to 25 feet of the horizon of this old surface.

THE FIELD EVIDENCE

Only a little of the evidence upon which the foregoing interpretations are based can be presented here. The exposures are in general poor, being found chiefly along roadside gutters. There are in Highland County three important localities for exposures of Hillsboro sandstone, and these are indicated on Figure 2. They are (1) at the east edge of Hillsboro at Lilley Hill; (2) in the north part of the

county near Samantha at Quaker Hill; and (3) in the southeast part of the county, 3 miles northwest of Sinking Springs, around a crossroads which will be known as Rhoads Corner.

LILLEY HILL

The exposure of Hillsboro sandstone at Lilley Hill, which is located at the east edge of the town of Hillsboro, may be considered the type locality, since Orton, in speaking of this exposure, wrote, "As a typical example of it [sandstone] occurs so near Hillsboro, it may be appropriately designated the Hillsboro sandstone."[1] He did not give a section of the exposure at Lilley Hill but stated that the sandstone had a thickness of 30 feet, capping the hill and resting upon the Niagara series. Prosser gave a section of the Lilley Hill exposure recording 9½ feet of sandstone resting on Cedarville dolomite (Niagaran) and with an unexposed interval of 7 feet above the sandstone to the top of the hill, or a maximum possible thickness of 16½ feet.[2]

The section now shown along the road on the east slope of Lilley Hill is as follows:

	Feet	Inches
4. Covered interval; to top of hill	7	
3. Hillsboro sandstone	4	6
2. Covered interval	15	
1. Niagaran dolomite	21	6
Contains pockets of Hillsboro sandstone at from 12 to 15 feet below the top of the zone.		

The Hillsboro sandstone exposure (zone 3) is small, but the sandstone is no doubt the highest bed rock and caps the hill. This sandstone capping Lilley Hill is an example of the first type of rock bodies noted above, that is, a remnant of the sheet deposit put down on the post-Greenfield erosion surface, which here was on the Niagaran dolomite.

The Niagaran (zone 1) contains pockets of sandstone. The exposures are along the gutters with Niagaran dolomite up the slope and down the slope, and the relations are such that one might, on general examination, very easily conclude that the sandstone is interstrati-

[1] *Geol. Survey Ohio, Rept. of Progress for 1870*, p. 306.

[2] *Amer. Jour. Sci.*, Vol. XLI (1916), pp. 445–46.

fied with the dolomite. When the exposures were dug out as completely as conditions warranted, the contact relations were found to be as shown in Figure 3. Figure 3*A* shows a sandstone exposure in the south gutter at about 15 feet below the top of the Niagaran of zone 1. The sandstone is exposed along the gutter for about 12 feet horizontally and the upslope end rises 2 feet above the gutter. The contacts are sharp, and there is not a grain of sand in the enclosing dolomite. At both ends of the exposure the dolomite passes over the top of the sandstone, but in the middle part of the exposure the dolomite above the sandstone has been weathered away.

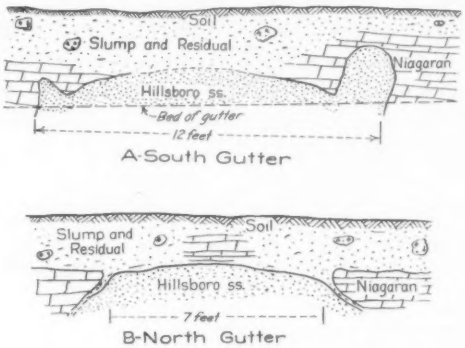

FIG. 3.—Sketches of exposures along the road on the east slope of Lilley Hill near Hillsboro, showing the upper parts of pockets of Hillsboro sandstone enclosed in Niagaran dolomite: *A*, south gutter; *B*, north gutter.

In the gutter on the north side of the road, at a slightly higher level, sandstone was exposed, which, when dug out, disclosed the relations shown in Figure 3*B*. It is 7 feet across the sandstone exposure along the gutter. The top of the sandstone drops in either direction along the gutter at angles of from 10 to 20 degrees, and walls of dolomite adjoin. Also in the bank above or beyond the gutter the dolomite was exposed. This is also the top of a sandstone mass, from which the overlying roof of dolomite has been removed.

Between the sandstone and the dolomite there is a thin layer, from 1 to 4 inches thick, of greenish gray, laminated clay, the lamination being concentric with the sandstone and dolomite walls. This

is not a residual clay from the weathering of the dolomite, but a clay carried in along this contact. Probably as the sandstone was consolidated it settled away from the wall and then clay was washed in, filling the space.

These two masses of sandstone belong to the class of cavity-filling described in the foregoing. The sand was washed down into and filled cavities in the dolomite from 15 to 25 feet below the erosion surface then existing, upon which the sandstone capping the hill was deposited.

SAMANTHA REGION

In the north part of Highland County, ½ mile west of Samantha, along a secondary road on the south slope of Quaker Hill is a poor roadside section that was studied by Orton[1] and by Prosser.[2] Orton considered this one of the most conclusive exposures showing the stratigraphic position of the sandstone, with Niagaran below and Helderberg (Monroe) above.

The section along the secondary road on the south slope of Quaker Hill is as follows:

	Feet	Inches
11. Covered interval; to top of hill just west of cemetery	9	
10. Ohio shale: black, fissile shale weathering to a brownish color	13	6
9. Covered interval	8	6
8. Greenfield dolomite: a single ledge in the east gutter	1	6
7. Greenfield dolomite: gray-drab, banded, somewhat argillaceous dolomite with *Hindella rostralis*, *Leperditia altoides*, and *Pentamerus pesovis*	5	6
6. Hillsboro sandstone: poorly exposed	3	
5. Covered interval with loose blocks of Greenfield dolomite	2	6
4. Greenfield dolomite with *Leperditia*	8	
3. Gray dolomite; probably Niagaran	2	9
2. Gray dolomite; Niagaran with sandstone pocket in lower part	3	3
1. Niagaran dolomite with *Pentamerus oblongus* and *Pycnostylus guelphensis*	11	

There are two sandstones in this section, one in the Niagaran (zone 2) and one in the Greenfield (zone 6), separated by about 15 feet of dolomite. Orton apparently considered all that part of the

[1] *Geol. Survey Ohio, Rept. Progress for 1870*, pp. 283–84, 307, and Fig. 4.

[2] *Amer. Jour. Sci.*, Vol. XLI (1916), pp. 437–45.

section indicated by zones 2 to 6, inclusive, as sandstone. Prosser published a section showing these two sandstones separated by dolomite, but did not designate the age of the dolomite.

The upper sandstone (zone 5) has Greenfield dolomite up the slope and down the slope. The contacts are poorly exposed, but were sufficiently well dug out to show that they dip outward from the sandstone. The exposure is poor, but the sandstone extends across the narrow roadway and covers most of the slope for about 3 feet vertically. It is the largest of the pocket masses known, being from 20 to 25 feet across in either direction, and is probably two or more masses close together, or the cavity was irregular with a large projection of dolomite hanging from the roof which comes down into the present exposure.

The lower sandstone (in zone 2) is a small mass 3 feet across exposed only in one gutter. The enclosing dolomite has weathered, in place, and we dug entirely under the mass which has a rounded uneven base.

Fifty yards west of this roadside section, exposures in some old, abandoned quarries cover the elevation of this entire section without showing any sandstone. Fifty yards to the east a large block of sandstone projects from the ground at the elevation of the covered interval (zone 9) below the Ohio shale, and may represent the sheet deposit on the post-Greenfield erosion surface.

In a ravine east of the road several masses of sandstone, more or less enclosed in the dolomite, project from the slope, and one vertical section shows a dikelike body of sandstone in a joint in the Greenfield dolomite. Dikes of this type were seen at several other places in Highland County, and at one place a surface exposure showed several intersecting joints in the Greenfield dolomite all filled with sandstone.

About 2 miles northeast of Samantha on the Jones farm (Fig. 2) the wall of a small quarry showed an irregular mass of sandstone, from 2 to 3 feet across enclosed in the Greenfield dolomite as shown in Figure 4. There is not a grain of sand in the enclosing dolomite, and this is one of the strongest cases in support of the cavity-filling interpretation. This pocket has at the base and the top some black shale very similar to Ohio shale.

RHOADS CORNER REGION

This locality is in the southeast corner of Highland County, 3 miles northwest of Sinking Spring around a crossroads known as Rhoads Corner (Fig. 5). Orton referred to this locality, and Prosser gave sections of several exposures here. There is here around Rhoads Corner the largest area of Hillsboro sandstone that is known. The sandstone caps the divides with thicknesses of from 10 to 20 feet over an area of a fraction of a square mile as shown in Figure 5. It belongs to the sheet deposit and rests on both the Niagaran and the Greenfield.

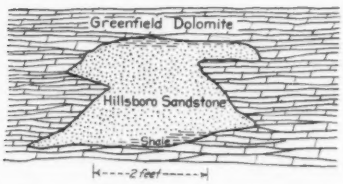

FIG. 4.—Sketch of an exposure in the Jones quarry 2 miles northeast of Samantha, showing a pocket of Hillsboro sandstone completely enclosed in the Greenfield dolomite.

There are also here several exposures of the sandstone pockets down in the dolomite. About 40 rods south of the crossroads and on the east of the road is a small quarry on the Stewart farm (see Fig. 5) that furnished one of Prosser's sections of the Hillsboro sandstone in which he showed dolomite above and below the sandstone.[1] A sketch of this exposure is shown in Figure 6. The enclosing stone is massive Niagaran dolomite without a grain of sand. The contacts are very sharp, and there are stringers of sandstone extending into the dolomite showing the irregularities of the walls of the cavity which was filled by the sand.

LABORATORY STUDIES

Microscopic and mechanical analyses were made of a number of samples of the Hillsboro sandstone and a few samples of the Sylvania sandstone.

MICROSCOPIC ANALYSES

The microscopic study dealt with the composition, the shape, the nature of the surfaces, and the secondary enlargement of the grains, and the mineral inclusions in the grains.

The Hillsboro sandstone is remarkably pure, the mineral quartz making up approximately 95 per cent of the entire rock. A very few

[1] *Amer. Jour. Sci.*, Vol. XLI (1916), pp. 446–48.

grains of tourmaline, garnet, and zircon, all exceedingly well-rounded, are present. A large number of the quartz grains, about 85 per cent of the more than 1,000 grains studied, show secondary enlarge-

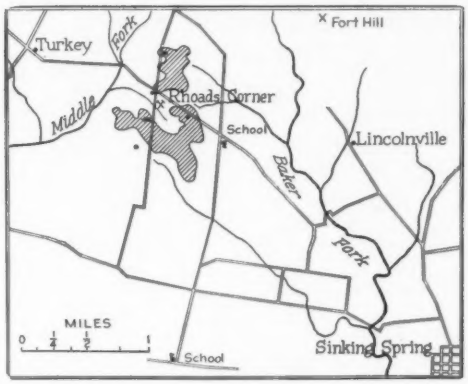

FIG. 5.—Map of the region around Rhoads Corner, showing the approximate area underlain by Hillsboro sandstone.

ment, the added quartz being clearer than the quartz of the original grain and separated by a thin film of iron oxide around the original grain. The new quartz is added in crystallographic orientation and optical continuity with the quartz of the original grain, and in many cases has formed definite crystal faces. A crystal showing double pyramidal terminations of the secondary growth of quartz is shown in Figure 7. Most of the original grains are somewhat elongate, and in nearly every case the secondary silica was added so as to make the long axis of the new crystal in the direction of the elongation of the original grain, showing that this elongation was in the direction of the long axis of the original crystal from which the grain was formed.

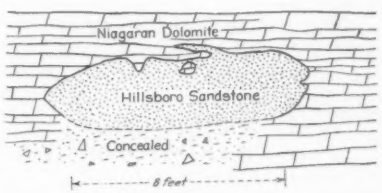

FIG. 6.—Sketch of an exposure in an abandoned quarry on the Stewart farm about 40 rods south of Rhoads Corner, showing a pocket of Hillsboro sandstone enclosed in the Niagaran dolomite.

The surfaces of the original grains are well pitted and frosted, a phenomenon which has commonly been considered indicative of eolian action at some time before the sand finally came to its present position. The secondary enlargement of the grains took place after the sand was deposited as the Hillsboro sandstone, for the faces and angles of the new quartz crystals show no wear whatever. No difference was detected in the secondary enlargement of the quartz grains in the sheet and cavity-filling types of deposits.

FIG. 7.—Photomicrograph of quartz grains from the Hillsboro sandstone, showing secondary enlargement. One of the grains, *A*, shows double pyramidal terminations of the crystal formed by the secondary growth of quartz about the original, rounded, pitted grain. The length of this quartz grain was increased about 40 per cent. Magnification about 100 diameters.

Hairlike needles of rutile are included in some of the original quartz grains, but in no case do they extend into the secondary enlargements, showing that the phenomenon of rutile-needle inclusion dates back to the crystallization of the original igneous rock from which the quartz grains were first derived.

Several samples of Sylvania sandstone from northwestern Ohio and southeastern Michigan were studied, and these show almost identical characteristics in rounding of grains, pitted and frosted surfaces, secondary enlargement, and even rutile-needle inclusions in the original quartz grains. The only difference detected is that the

grains of the Hillsboro sandstone are somewhat smaller and show more secondary enlargement than those of the Sylvania sandstone.

MECHANICAL ANALYSES

The Hillsboro sandstone is very friable and separates easily into grains suitable for mechanical analysis. A known weight of each sample was agitated in a rotary screening machine with a series of screens and the sand remaining on each screen weighed to determine the percentage distribution. The table given here shows the percentage distribution of the samples on the basis of the size of grains, and the same data are shown graphically in Figure 8.

In the table and in Figure 8, the samples are indicated by numbers and the locations for these samples are as follows:

1. Hillsboro sandstone from the ledge at the crest of Lilley Hill.
2. Hillsboro sandstone from the pocket in the south gutter on the east slope of Lilley Hill.
3. Hillsboro sandstone from the upper pocket on the south slope of Quaker Hill.
4. Hillsboro sandstone from the pocket in the Jones quarry 2 miles northeast of Samantha.
5. Hillsboro sandstone from the ledge in the field northeast of Rhoads Corner.
6. Hillsboro sandstone from dike in Greenfield dolomite north of Rhoads Corner.
7. Hillsboro sandstone from pocket in the Stewart quarry south of Rhoads Corner.
8. Sylvania sandstone from a quarry near Silica, Lucas County, Ohio.
9. Sylvania sandstone from a quarry in Monroe County, southeastern Michigan.
10. Sylvania sandstone from a quarry in Monroe County, southeastern Michigan.

Size in Mm.	Hillsboro Sandstone							Sylvania Ss.		
	Lilley Hill		Samantha		Rhoads Corner			Lucas County	Southeastern Michigan	
	Sheet	Pocket	Pocket	Pocket	Sheet	Dike	Pocket			
	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8	No. 9	No. 10
2–1	.....	.....	.....	0.10	.....	.....	.....	.....	.....	0.06
1–$\frac{1}{2}$	0.04	0.06	.....	0.22	0.06	0.10	0.06	0.20	0.60	0.74
$\frac{1}{2}$–$\frac{1}{4}$	1.12	3.70	1.62	10.06	0.56	2.24	5.36	20.44	77.12	77.78
$\frac{1}{4}$–$\frac{1}{8}$	38.50	37.44	17.10	42.66	15.62	45.76	42.16	69.44	16.12	17.50
$\frac{1}{8}$–$\frac{1}{16}$	58.56	54.66	73.80	42.96	81.42	48.82	48.82	9.24	3.80	3.34
$\frac{1}{16}$	1.10	3.82	6.90	3.36	2.32	2.90	2.96	0.24	0.82	0.56

As shown by the table and Figure 8, over 90 per cent of the grains of the Hillsboro sandstone fall into the two compartments between

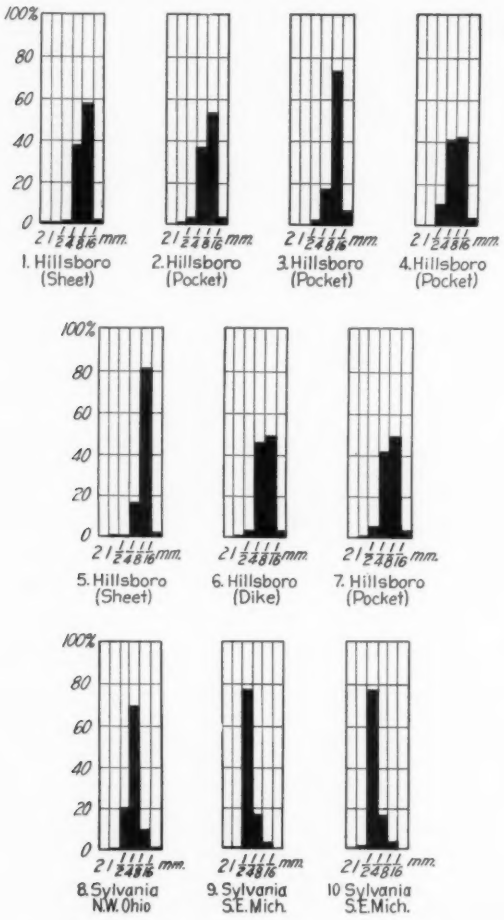

FIG. 8.—Composition pyramids, showing by percentage distribution the size of the grains and the degree of sorting for various samples of Hillsboro sandstone (1 to 7) and Sylvania sandstone (8 to 10).

$\frac{1}{4}$ mm. and $\frac{1}{16}$ mm., giving a remarkably even-grained sandstone. In all cases the percentage falling into the smaller of these two compartments, $\frac{1}{8}$ mm. to $\frac{1}{16}$ mm., is somewhat larger, and in two samples (Nos. 3 and 5) it is several times larger. The average size of the grains of the Hillsboro sandstone is, therefore, slightly under $\frac{1}{8}$ mm., a very fine-grained sandstone. However, the secondary enlargement of the grains is estimated to have increased their size about 20 per cent and to have affected about 85 per cent of the grains, so that the average size of the grains of the Hillsboro sandstone at the time of deposition was about $\frac{1}{10}$ mm. No essential difference in the size of the grains of the sheet and cavity-filling types of deposits exists. The Sylvania sandstone (Nos. 8, 9, and 10) is somewhat coarser, about 90 per cent of the grains falling into the two compartments between $\frac{1}{2}$ mm. and $\frac{1}{8}$ mm., with an average size, as judged by the three analyses, of slightly over $\frac{1}{4}$ mm.

THE AGE OF THE HILLSBORO SANDSTONE

When the supposed cases of interstratified Hillsboro sandstone with the Niagaran and the Greenfield dolomites are eliminated by the cavity-filling interpretation, the remainder of the exposures fall into the class of bedded sandstone, laid down disconformably upon the eroded surface of Greenfield and Niagaran dolomites in post-Greenfield time. The next overlying formation in this region is the Ohio shale. Therefore, the hiatus within which the Hillsboro sandstone exists, extends from the Greenfield of Upper Silurian (Cayugan) age through the Lower and Middle Devonian to the Ohio shale of Upper Devonian age. All the intervening formations of Lower and Middle Devonian of central and northern Ohio, with a total thickness of at least 500 feet, are absent in Highland County.

Within the hiatus in which the Hillsboro sandstone exists are the Sylvania sandstone of earliest Devonian age of northwestern Ohio; the sand-containing, basal layer of the Columbus limestone of Middle Devonian age in Central Ohio; the upper water horizon of the Big Lime of eastern Ohio, as known by well records; and the Oriskany sandstone. Is the Hillsboro the correlative of any of these?

No source for the sand of the Hillsboro sandstone is known in this southern part of Ohio. There is nothing in the older rocks that might have furnished the sand. It may have been brought in from the east as the thinning edge of the Oriskany or the upper water horizon of the Big Lime, or it may have come from the north, trailed out from the Sylvania sandstone of northwestern Ohio. The close similarity of the Hillsboro and Sylvania sandstones in composition, degree of rounding of grains, pitted and frosted surfaces of grains, secondary enlargement, and rutile-needle inclusions have been noted in the foregoing, and the authors believe that these two sandstones had a common origin.

The deposition of the Hillsboro was sufficiently long after Greenfield time that the Greenfield was largely removed, so there can be little question but that the Hillsboro is at least as late as the beginning of the Devonian period. In several of the cavity-filling masses, a dark to black shale, which can hardly be distinguished from the Ohio shale, is associated with the margins of the sandstone masses, suggesting that the sandstone was deposited just before the Ohio shale, in the encroaching sea which inaugurated the Ohio shale deposition. The Hillsboro probably represents some of the finer sand of the Sylvania, shifted southward by wind and water during the long Silurian-Devonian erosion interval which, in Highland County, apparently lasted until Upper Devonian time. It was lying on the surface when the Upper Devonian sea invaded the region, bedded the sand, and washed some of it down into the cavities beneath the surface.

SUMMARY AND CONCLUSIONS

In summary, the points which have been stressed in this article are as follows:

1. The Hillsboro sandstone is interpreted as including two types of deposits: (*a*) bedded sandstone resting on either the Niagaran or the Greenfield dolomites; (*b*) masses of sandstone which are cavity-fillings enclosed in either the Niagaran or the Greenfield dolomites. Examples of both types have been described.

2. The Hillsboro sandstone exists in a hiatus which extends from the Greenfield dolomite of Upper Silurian to the Ohio shale of Upper

Devonian. The presence of black shale, almost identical with the Ohio shale, around the margins of some of the sand masses indicates that the deposition of the sand took place just before the deposition of the Ohio shale in Upper Devonian time.

3. In both physical and microscopic characteristics the Hillsboro sandstone is almost identical with the Sylvania sandstone of basal Devonian age in northwestern Ohio. It probably represents some of the finer sand of the Sylvania shifted southward during the Silurian-Devonian erosion interval which, in Highland County, lasted until Upper Devonian time.

THE RÔLE OF SOLUTION IN PENEPLANATION

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ABSTRACT

The discussion is confined to the lowest (Somerville) peneplain of eastern Pennsylvania. The usually accepted origin by stream erosion is questioned by citing six opposing lines of evidence. Solution as a dominant process is considered to meet the facts best.

In describing the physiography of eastern Pennsylvania much emphasis has been placed (and rightly so) upon its series of peneplains. Three prominent successive degradation surfaces are striking features of the landscape, appreciated even by those with but little geological training; in fact, they are classic illustrations of the effects of successive periods of erosion and uplift. The literature is full of references to these so-called peneplains, but there is no complete agreement as to the details of their origin. Usually they are cited as fine examples of the normal or fluviatile type of origin. Yet Barrell[1] has offered strong arguments for a marine origin. More recently Stose[2] has suggested that, instead of three peneplains, one is part of another faulted down.

The writer believes that it is quite possible that there were only two cycles of stream erosion and that the lowest level (Somerville)[3] may have had another origin. It is the purpose of this article to present the evidence for this belief and then suggest an alternative hypothesis of origin. The writer's direct observations in reference to this topic have been in the territory between Easton and Lebanon. A wider study may modify the conclusion reached.

[1] J. Barrell, "Piedmont Terraces of the Northern Appalachians and Their Mode of Origin," *Bull. Geol. Soc. Amer.*, Vol. XXIV (1913), pp. 688–96; "Piedmont Terraces of the Northern Appalachians," *Amer. Jour. Sci.*, Vol. XLIX (1920), pp. 227–58, 327–62, 407–28.

[2] G. W. Stose, "Possible Post-Cretaceous Faulting in the Appalachians," *Bull. Geol. Soc. Amer.*, Vol. XXXVIII (1927), pp. 493–504.

[3] On the back of the Delaware Water Gap sheet, the three peneplains are named Kittatinny (highest), Schooley (middle), Harrisburg (lowest). Later usage is, Schooley (highest), Harrisburg (middle), Somerville (lowest), which is the nomenclature followed in the present article.

ORIGIN BY STREAM EROSION

The matter may perhaps be best approached by presenting several objections to the time-honored belief in the effectiveness of stream erosion for this Somerville surface, as follows:

1. *Areal distribution of the Somerville.*—A striking fact about the occurrence of the Somerville surface is its restriction to areas of limestone. This is the case around Easton, westward to Lebanon, and beyond. The width varies as the limestone varies: it is widest (10 miles) near Easton, about 7 miles wide in the vicinity of Allen-

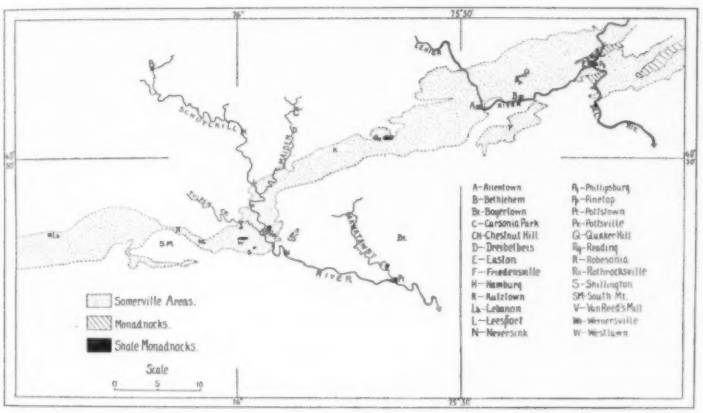

FIG. 1

town and 2 to 3 miles from Kutztown to Reading and beyond. At Wernersville it is a little over a mile in width, and about a mile west of Robesonia it is less than a half-mile. Beyond this narrow neck it again widens, becoming 5 miles wide near Lebanon.

From this general larger occurrence extend embayments: the Somerville surfaces at Easton and Phillipsburg (New Jersey) are of this sort, also the "coves" bordering the Delaware below Easton. The Friedensville valley farther west is another example. A similar occurrence is near Boyertown, another north and northeast of Rothrocksville. South Mountain, west of Wernersville, is nearly surrounded.

Then there are separated portions, or "islands": the suburb east of Reading where Carsonia Park is located is such a case. The lowland between Reading and Boyertown, through which Manatawny Creek flows, is another. A third "island" is the district around Morgantown.

All this larger Somerville "peneplain" and its embayments and "islands" are developed on limestone alone, whereas the adjoining higher peneplained areas are on various kinds of rocks. To require running water to be so selective seems to be stretching probability to the breaking-point.

2. *Topography.*—Elevation since formation of the Somerville degradation surface has naturally produced dissection and corresponding destruction of part of the original surface. But since the Somerville is the youngest of the peneplains it should have retained more of its original characteristics than any of the others. And such is the case; there are good-sized areas that are nearly flat, or gently undulating or rolling.

There is no major stream incised and running the length of this rather extended area, except a short section of the Lehigh River between Allentown and Easton, and a portion of the Schuylkill near Reading, the latter running as much across as with the limestone lowland. This does not prove a great deal. But if an erosional surface with very considerable length compared to its width has been made by stream action, one would expect more incised remnants of it to be present. These are conspicuously absent.

If one examines the Princeton, Indiana, or New Haven, Illinois, topographic sheets, one gets a picture of the topography of an old-age valley about the width of the Somerville area considered. If such a valley were uplifted so that rejuvenation of stream action occurred, one would expect these large streams to be incised. If the elevation was differential, only portions of the streams would be so affected, but the non-incised portions ought to show their one-time old-age characteristics. Even if dissection advanced as far as it has in the Somerville area, the fragments of the old-age valley ought to show enough continuity to prove the type of origin. There is absolutely none of this sort of a record in the Somerville area: no remnants at all of former through valleys. There are many small shallow valleys

with dendritic tributaries. What is more significant is the fact that there are abundant sink holes and solution basins.

3. *Monadnocks.*—A peneplain commonly has monadnocks, and this Somerville surface has several. Chestnut Hill near Easton, Pine Top, and Quaker Hill north of Bethlehem are some. These are made of rather resistant pre-Cambrian rock. Farther west there are several composed of shale—the hill in the north part of Reading and on which the Charles Evans Cemetery is located is one; others are north of West Lawn, south of Van Reeds mill, and northeast of Shillington. Monadnocks, particularly on large peneplains, would naturally be of harder material. On smaller and narrower peneplains, such as the one considered, there might well be some composed of the same material in which the peneplain proper is cut, having the advantage of position, being the last portions to go. There are no limestone monadnocks in this area, and one or two might reasonably be expected. Then what about the shale monadnocks? Shale can hardly be called a resistant material. Shale is not hard, nor tough, nor strong. Limestone is slightly harder than shale and is immensely tougher and stronger. Those who use concrete for structural and highway work condemn coarse aggregate that contains shale, but, in contrast, crushed limestone is universally used in this region.

On this Somerville peneplain, then, there are no limestone monadnocks, but there are shale monadnocks, which is inconsistent with the concept of a peneplain made by the eroding power of running water.

4. *Absence of tools.*—If a peneplain has been made by stream action, there is the necessary assumption that tools were used by the stream. The most effective tools are gravels of various sizes, cobbles, etc. After rejuvenation, patches and larger-sized stretches and beds of these tools may be expected to remain over part of the peneplain surface. These tend to persist because of two qualities they possess: one is that tools are made of the more resistant materials. The very process of stream erosion over such length of time implied in the word peneplain is selective of resistant rock fragments. The second quality is the texture of such a bed of fragments. The porous quality of a gravel bed minimizes run-off and hence removal, even in exposed positions.

As a partial test of the persistence of tools under such conditions, the writer examined a few places along the Raystown Branch of the Juniata River. The clearest case of two cycles of undoubted stream action is to be found in entrenched meanders. It is evident that the stream formerly flowed at the level now marked by the crests of the spurs between meanders. Such being the case, one would expect to find tools along the crests of these spurs marking the bottom of the old valley. A number of these spur-crests were examined. On the wide-topped spurs plenty of tools were found; on the crests of lesser area, no tools at all were found on the narrow, ridgelike ones, while scattered tools were found with difficulty on the ridges whose summits had a little width. From this it seems plain that if the peneplain remnant is only of moderate size the tools easily remain, and that if the remnant is narrow the removal of tools by subsequent erosion is easy.

Let us apply this criterion to the Somerville erosion surface. During several field seasons the writer has been employed by the Pennsylvania Geological Survey to study the sand and gravel resources of the state. This necessitated careful search in regions where these materials were scarce. For instance, several weeks' time was spent in the Reading region, and the whole lowland (Somerville peneplain) from near Allentown to well beyond Reading was gone over carefully. Other parts of the Somerville were studied as well. Not a single bed of sand or gravel was found along some 20 miles of the lowland which received this close scrutiny, nor on any part of it that was examined less thoroughly. Comparison of the areas of the Somerville remnants and the remnants on the Juniata spurs reveals the fact that Somerville remnants five times the area of the spur remnants are common and even larger remnants not rare. On the basis of size of remnants alone, every advantage should be with the Somerville. While no beds of gravel were found, water-worn, hard tools were found scattered in a very few localities.

Another phase of the persistence or non-persistence of tools needs to be presented: rock substances not removed mechanically by erosion may be removed, though more slowly, by decomposition and solution. Even granting this, there remains the additional fact that

river tools made very largely of hard, quartzitic material are very resistant to this process. Furthermore, a bed of river gravels subject only to weathering and decomposition would retain its entity from the standpoint of structure though the individual fragments were affected by decomposition to such a degree that they would crumble to pieces under the hand. Nothing of this sort was encountered. What is more, the few scattered tools found were not weathered to any such degree or near it; they were still tough and strong.

The writer does not mean to insist that there were no streams at all on this Somerville peneplain. There must have been some; indeed, the few tools found prove there were some. And real beds of tools may be found on those portions of the Somerville not visited by the writer. But the evidence outlined strongly suggests that there were no large and prominent streams, in other words, that stream erosion was probably not a dominant process in the making of the Somerville peneplain.

5. *Some characters of present-day streams.*—If we agree that the width of a given valley is a measure of the erosive power of the stream and the erodability of the rock encountered, we will find it instructive to compare the valley of a given stream in various parts of its course.

The Schuylkill River has cut a trench below the level of the Somerville, but the width of its valley (the valley flats) varies from place to place. From Hamburg to Leesport the width is greater than from Leesport to south Reading, further down stream (see Hamburg and Reading sheets). It is significant that the wider part has developed on shale and the narrower part on limestone. North of Hamburg the harder sandstones have determined a narrower valley. Below Reading (along Neversink Mountain and adjacent ridges) for a short distance, the influence of harder materials has again made the valley narrower. The valley widens again, starting near the station of Neversink, and maintains its width down to below Pottstown, where it narrows again. This latter stretch of wider valley is again developed on shale (Triassic), while the Triassic below Pottstown is sandier and so more resistant.

The valley of Maiden Creek, tributary to the Schuylkill, shows

similar differences. The upstream portion, from Dreibelbeis down for some miles, is wider and is developed on shale. The lower part in the Somerville area is narrower and is developed on limestone.

Tulpehocken Creek is wider upstream than it is downstream, where it flows on limestone.

While other interpretations can be invented to explain the foregoing facts, the logical one is that limestone does not erode as easily as shale does, an explanation that fits in with the other evidence so far presented in the discussion of the origin of this peneplain.

6. *Condition of surface of the limestone.*—The limestone on which the Somerville has been developed is shown in section by an abundance of quarries and railroad cuts. Opportunity is thus given to examine the condition of the surface of the limestone and see whether any evidence of stream erosion is shown. Nowhere is there evidence of channeling or any surfaces of abrasion. On the contrary, the limestone shows the small irregularities so commonly developed by solution everywhere in limestone regions.

7. *Conclusion.*—The six types of evidence presented here point in the same direction, are cumulative, and indicate that stream erosion had little part in producing the Somerville peneplain.

ALTERNATIVE METHODS OF ORIGIN

The Somerville surface certainly exists and some process of degradation must have operated to produce it.

1. The most obvious process is solution. It is of course well known and accepted as a fact that limestone is the most soluble of our common rocks. Evidence for solution and deep weathering is abundant in the area under consideration. Sink holes and saucer-shaped depressions are common. Many are large enough to show on the topographic maps, particularly the Reading and Slatington sheets. Many others are too shallow to be represented by the 20-foot interval. The cover resting on the limestone is universally the residual type of accumulation with the uneven surface of solution below it and averages from 4 to 8 feet in thickness.

Many of the smaller valleys are found to terminate upstream in a widened head, or are rather wide-floored and consist of connected, shallow sinks. This suggests that the valleys developed as a series of

breached, adjoining sink holes, or that that solution is so much more active than erosion that sink development is outstripping the stream erosion in the valleys started by stream erosion.

In several places new, well-like sinks have been seen to develop during the last year, indicating that solution locally is much more rapid than even the removal of soil by running water.

At one place where the limestone area abutted abruptly against a prominent upland, wash from the upland had covered the limestone with from 5 to 12 feet of débris. And yet in the midst of this débris a sink had formed. Obviously deposition was dominant over erosion at this place, yet active solution continued in the limestone below.

In another locality a rather deep pit (the top of which is at the Somerville level) had been opened to secure commercial sand and gravel. The deposit was found to be resting on limestone. All the drainage from this pit and the water from heavy rains disappears at once through holes in the limestone below—another evidence of solution.

It is interesting to note that the shaly or impure limestone (like the Jacksonburg or "cement rock") has a topographic position intermediate between the ordinary limestone (lower) and the ordinary shale (higher).

The adjoining higher (topographically) rocks of the region, such as granite, gneiss, quartzite, quartz schist, diabase, are deeply weathered to depths of from 10 to 30 feet. Though in higher positions and on steeper slopes, the erosion has not removed material very rapidly. Solution has done what it could but could remove only a fraction of the total. The upland ridges are ridges because of their resistance to both erosion and solution. The limestone could resist the erosion, what little there was of it, but could not withstand the solution.

It would be interesting to make comparative tests on higher and lower portions of the generally flat to undulating limestone lowland. We venture the prediction that chemical analysis of these parts of the limestone would show the lower portions to be of purer limestone than the higher portions, in other words, that there is a close relation between the elevations and purity and solubility of the limestone, within the limestone area itself.

It is logical to believe that erosion helped in making the Harrisburg peneplain. Since that time the portion of the Harrisburg peneplain underlain by limestone was reduced to the Somerville level chiefly by solution. Naturally some erosion accompanied the solution, but it would consist more of rain wash and small streamlet action immediately tributary to the trenching following uplift, with moderate-sized streams at infrequent intervals. In the present cycle, erosion of rocks outside the limestone area will not keep pace with solution on the limestone area until the latter has reached a position near baselevel.

The earlier history would be similar. Denudation following the uplift of the Schooley peneplain would combine the two processes of erosion and solution, the latter outstripping the former in point of time, the former eventually catching up with the latter when the solution surface had been stabilized by attaining baselevel—the completed Harrisburg peneplain being the final product till renewal of the uplift started the two processes to work differentially again.

2. No doubt faulting would account for some of the eccentricities of the limestone distribution. Undoubted faults exist. Others are suggested. But as a general explanation of the facts presented faulting would hardly serve.

THE SIGNIFICANCE OF THE QUARTZITES OF PINE MOUNTAIN IN THE CRYSTALLINES OF WEST CENTRAL GEORGIA

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ABSTRACT

The quartzites and schists in Pine Mountain, Georgia, are a continuation of a belt of rocks in Alabama which includes quartzites, dolomites, schists, and amorphous graphite. The lineal extent of the belt is 100 miles, 70 miles of which lie in Georgia. The age of the formations is uncertain, but is probably Paleozoic. Their geographic position has an important bearing on the paleogeography of the region. They imply a shore line far to the east of any which have been conjectured for Paleozoic seas in the region.

INTRODUCTION

The Pine Mountain district in the Greenville Plateau of western Midland Georgia includes Pine Mountain and Oak Mountain, which are steep-sided curvilinear ridges standing in such bold relief as to challenge the attention of the casual observer and incite a geologist to investigate their origin. These mountains are defined for the most part by the 750-, 1,000-, and 1,250-foot contours and rise from 200 to 400 feet above the surrounding upland.

The writer became interested in the Pine Mountain district while studying the Hollis quartzites in Alabama in 1924. These rocks occur as lineal remnants in the crystallines and have only moderate topographic expression. Since they trend toward Pine Mountain, it was conjectured that the quartzites are responsible for the ridges and knobs in the Pine Mountain district of Georgia. In crossing the district on the line of the Southern Railway which passes through Warm Springs, the writer saw that quartzites are conspicuous there and suggested that the Hollis quartzites in Alabama may be the equivalent of those in Pine Mountain and Oak Mountain in Georgia.[1]

The Hollis quartzites were discussed with LaForge, who, in describing the physiography of central Georgia, stated that the ridges of the Pine Mountain district owe their existence and form to belts

[1] George I. Adams, "Geology of Alabama," *Special Report No. 14, Geol. Survey of Alabama* (1926), "Crystalline Rocks," p. 34.

and lenses of coarsely granular quartzites, and that the rocks extend into Alabama, where they are in rather thin layers interbedded with much less resistant rocks and hence do not form bold ridges, but belts of rough ground which rise only a little above the upland.[1]

While studying the crystalline rocks for the Geological Survey of Alabama in the summer of 1929, the writer found some additional exposures of the Hollis quartzites, and, after the close of that work, made a brief reconnaissance in the Pine Mountain district. This article summarizes what has been published concerning the Hollis quartzites and associated rocks, contributes a few new facts, and discusses the significance of the formations.

The first mention of the rocks here discussed as the Hollis quartzites was by Tuomey,[2] who in 1858 described exposures of stratified quartzose rocks which he called itacolumite, a rock which he stated was first recognized by Humboldt in South America. Some of the Hollis beds are slightly flexible micaceous quartzites or itacolumites, but this variety is rare. Tuomey also reported the occurrence of limestones and bold limestone springs adjacent to the quartzites. The rocks which he called limestones are shown by the analyses in his report to be dolomites. Prouty has referred to them as the Chewacla dolomite marble.[3]

Dr. Eugene A. Smith, who succeeded Tuomey as state geologist of Alabama, in his first report published in 1874, while reviewing the localities seen by Tuomey, described the Chewacla quarry (referred to as the Yonge's quarry by Tuomey) and expressed the opinion that the dolomites lie to the southeast of an anticlinal fold, but very near its summit,[4] thus confirming in general the statement by Tuomey that the strata dip to the right and left of the trough-shaped depression in which the rocks are found. Of particular interest is Dr. Smith's section on Chewacla Creek near Wright's Mill, in which porphyritic gneiss is described as occurring between beds of quartzites.[5]

[1] Lawrence LaForge, "Physical Geography of Georgia," *Geol. Survey of Georgia, Bulletin 42* (1925), p. 79.

[2] M. Tuomey, *Second Annual Report, Geol. Survey of Alabama* (1858), pp. 51 ff.

[3] W. F. Prouty, *Geol. Survey of Alabama, Bulletin 18* (1916), p. 94.

[4] Eugene A. Smith, *Geol. Survey of Alabama, Report of Progress for 1874*, p. 105.

[5] *Ibid.*, p. 111.

LOCALITIES IN ALABAMA

The following is an annotated list of all localities in Alabama at which the quartzites discussed in this article have been found. Dolomites have been found at two of the localities as noted. The numbers of the localities correspond to the numbers shown on Figure 2. The references are to the reports of Tuomey and Smith cited in the foregoing:

1. Vaughn's Mill, formerly Ferrell's Mill, near Sec. 30, T. 18 N., R. 25 E. Beds of quartzite. No dolomite, but bold springs near by

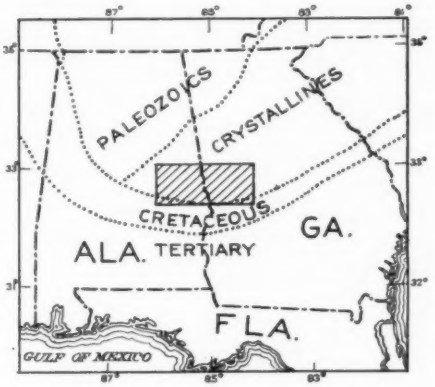

FIG. 1.—Index map, showing the position of Figure 2

suggest its presence. The locality lies within the border of the Upper Cretaceous. (Tuomey, p. 51; Smith, p. 114.)

2. Wright's Mill. Exposures in and near Sec. 18, T. 18 N., R. 26 E. The area includes Echol's Mills and Echol's quarry. Exposures of dolomite and quartzites, the latter intruded by porphyritic gneiss. (Tuomey, pp. 55–56; Smith pp. 111–13.)

3. Chewacla quarry, formerly Yonge's quarry. The type locality for the Chewacla dolomite. Sec. 4, T. 18 N., R. 27 E. To the northeast of this quarry are Colquit's quarry, Springvilla, and additional exposures, including the type locality of the Hollis quartzite, which is near a siding at a water tank on the Central of Georgia Railway. (Tuomey, pp. 52–54; Smith, pp. 104–9.)

4. Mountain Spring Church, on the line between Sec. 10 and Sec. 15, T. 19 N., R. 28 E. Exposures of thin-bedded quartzites extend for over a mile to the southwest and southeast from the church.

5. Halawakee Creek bridge. New locality in Sec. 36, T. 20 N., R. 28 E. Good exposures at the south end of the bridge. In front of the store at the north end of the bridge the quartzites are intruded by a much weathered igneous rock, which appears to be like that at locality No. 2.

6. Half-mile south of Jester. New locality; eastern part of Sec. 29, T. 20 N., R. 28 E. Good exposures of quartzites in the hills to

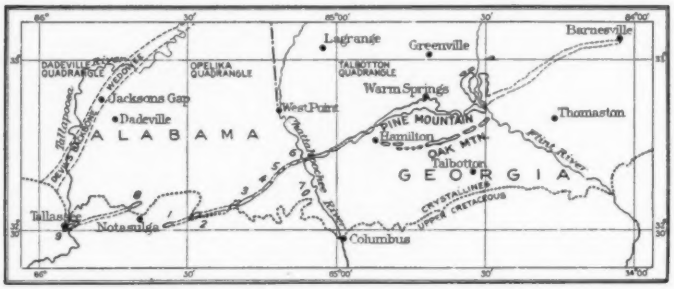

FIG. 2.—Sketch map, showing the extent of the belt in which the Hollis quartzite has been found.

the west and east of the road. Just to the north of the quartzites a bed of amorphous graphite in schists is exposed.

7. Roadside one-half mile north of Soapstone Creek. New locality; NE. $\frac{1}{4}$ Sec. 25, T. 19 N., R. 29 E. Some thin quartzites but mostly light-colored argillites that could easily be taken for Coal Measure clays. Such beds were also seen at Wright's Mill, locality No. 2, at the east end of the bridge.

8. Ragan's Mill, north of Notasulga. At this place Tuomey (p. 51) saw "slates passing into itacolumite." Smith states (p. 94) that below the mill the mica schists became more quartzose and assume the characters of itacolumite.

9. Tallassee. The section for this locality by Smith (p. 95) includes itacolumite, some specimens of which are fairly flexible, and

arenaceous, or quartz mica schists passing below into itacolumite. It is probable, as Smith suggests, that Tallassee and Ragan's Mill localities lie in the same belt of rocks.

OBSERVATIONS IN GEORGIA

The quartzites of Pine Mountain, Georgia, were seen by the writer at the following places: a few miles east of the Alabama line; on the highway south of Warm Springs; to the southwest of Warm Springs for 5 miles; to the east of Warm Springs to the border of the Talbotton quadrangle. On the high point 5 miles southwest of Warm Springs there are massive beds of quartzites, and similar beds were seen on the isolated knobs in the northeast corner of the Talbotton quadrangle. In most of the exposures the quartzites are relatively thin bedded. Mica schists are interbedded with the quartzites at many places. The structure of Pine Mountain south of Warm Springs is anticlinal. The mountain, however, is not anticlinal throughout its extent, for faults were seen in the quartzites and monoclinal structure was noted. No intrusion of igneous rock in the quartzites in Georgia was observed.

The continuation of Pine Mountain to Barnesville was not studied. The general position of the knobs and ridges is indicated very roughly by dotted lines in Figure 2. At Barnesville the quartzites seen along the road that leads to the water works are monoclinal. Some of them are weathered to a loose granular rock in which the mica is conspicuous. The quartzites are interbedded with platy mica schist and garnet mica schist. Possibly the quartzites extend eastward from Barnesville, but the knobs and ridges end there.

Dolomites are not known to occur in association with the quartzites in Georgia, but the state geologist of Georgia, S. W. McCallie, has called my attention to the existence of strong springs at several places near the quartzites and shown that the analyses of waters from these springs suggest that there may be dolomites associated with the quartzites.

AGE OF THE QUARTZITES

The age of the Hollis quartzites is difficult to determine. They are not known to contain fossils, and they are not continuous with similar rocks of known age. The Chewacla dolomites associated

with the quartzites have yielded no fossils. The Jumbo dolomite member[1] in the upper part of the Talladega occurs about 65 miles to the west, and like the Chewacla dolomite is found only near the southern border of the crystallines close to the Cretaceous overlap. It is 13,500 feet below the top of the Talladega formation, which is calculated by Butts to be 30,000 feet thick. According to Butts, who bases his reasoning on the occurrence of Devonian invertebrates and Carboniferous plant fossils, the upper part of the Talladega is Devonian and post-Devonian. The Jumbo dolomite lies 1,000 feet below the Devonian part of the Talladega. If the Chewacla formation is the equivalent of the Jumbo member, the age of the Hollis quartzites which are above the Chewacla dolomites is approximated by the correlation.

About 4,500 feet above the base of the Talladega there are limestones from 100 to 500 feet thick (Sawyer limestone, gray limestone with Cryptozoon or Graysonia, and the Sylacauga marble), but these do not correspond to the Chewacla lithologically. With the exception of the very limited occurrence of marble at Dempsey, and this is possibly 2,000 feet stratigraphically higher than the Jumbo dolomite, no other limestones or dolomites are known in the crystallines of Alabama.[2]

The Lower Devonian (Oriskany) Jemison chert described by Butts[3] may be considered in this connection. It is at least 500 feet thick, but it is not known whether it was a dolomite or a limestone in its original state. It is succeeded by the Yellow Leaf quartz schist, which has a known thickness of at least 500 feet and varies in character from an argillite to a fine-grained sandstone, but has a

[1] Charles Butts, "Geology of Alabama," *Report No. 14, Geol. Survey of Alabama* (1926), "Paleozoic Rocks," p. 53.

[2] It may be noted here that the statement by Tuomey (p. 71 of his report already referred to), that marble occurs some miles east of Delta, is seemingly erroneous. Dr. Smith informed the writer that the locality has been searched and no marble found. The writer has also made inquiries, and no one there knew anything about such an occurrence. Likewise, it may be remarked that the name of the old post-office of "Lime" in the southeastern corner of Randolph County has no geological significance. It is said that it was intended to name the post-office "Line" because of its proximity to the state line.

[3] *Ibid.*, p. 145.

well-defined schistose structure. The correlation of the Chewacla marble and the Hollis quartzites with these formations is, to say the least, problematical.

Last summer when the writer found the Hollis quartzites at the easternmost locality in Alabama (No. 6 in Fig. 2), he also found an outcrop of amorphous graphite in schists which were near the quartzites. Amorphous graphite beds in Alabama have thus far been regarded as occurring rather high in the crystallines, and their presence in the belt containing the Hollis quartzites accordingly implies a relatively late age for the associated rocks.

If reference is made to the geologic mapping of the crystallines in various quadrangles in North Carolina, Tennessee, and the northern border of Georgia, it will be seen that the metamorphosed sediments there are referred to the Cambrian. These rocks are too distant to afford a basis for correlation. Moreover, the structures in the quadrangles to the north do not extent toward the Pine Mountain district, and the trend of Pine Mountain is divergent. Cambrian rocks in Alabama are found to the west of the great thrust faults which define the northwestern border of the crystallines, but their presence or equivalents have not been identified to the east of these faults.

PALEOGEOGRAPHIC SIGNIFICANCE

The age of the formations under discussion is not definitely known.[1] The writer, however, is here considering them to be Paleozoics and possibly well above the base of the Paleozoic section. If this interpretation is correct, it implies a transgression of the Paleozoic seas to the eastward, or an embayment from the southwest.

Butts[2] has stated that the Devonian and Carboniferous formations succeed older and older rocks from west to east across Alabama, so that they might have been deposited upon rocks of Cambrian age or even older in the eastern part of the state. He, however, may not favor the suggestion that the Hollis quartzites are rather

[1] The Hollis quartzites and Chewacla dolomite were tentatively referred to the Algonkian in *Report No. 14 of the Geol. Survey of Alabama*, but for no adequate reason. The writer has explained that in the report he presented largely a sympathetic interpretation of the work and opinions of others.

[2] *Ibid.*, p. 61.

late Paleozoics or agree to the extension of any Paleozoic overlap 70 miles or more into Georgia.

The crystallines in Alabama southeast of the Devil's Back Bone strip of the Wedowee (see Fig. 2) were shown on the recent geologic map of the state as Archean, with the legend, "Igneous schists and gneiss and, as mapped, including younger intrusive rocks and infolded metamorphosed sedimentary rocks." The formations under consideration here are part of these metamorphosed sediments which in two localities have been intruded by a porphyritic gneiss. Special interest attaches to them because they lie on what has generally been called Appalachia and far to the east of the limits assigned by paleogeographers to any Paleozoic sea.

According to the generally accepted history of Appalachia, the processes which supplied sediments to the Appalachian geosyncline wore down the western margin of the old land area. A wider transgression of the seas to the eastward was thus made possible. If the rocks discussed in this article are of Paleozoic age and at the base of the section, then it would be appropriate to remove the Lower Cambrian mountains shown on certain paleogeographic maps as lying in eastern Alabama and in Georgia. If they are above the base of the section, then the later Paleozoic seas should be extended eastward on the paleogeographic maps. It is highly improbable that the positions of the ancient shore lines far into Paleozoic time should be placed to coincide with the thrust faults which define the western border of the crystallines.

It was stated in the beginning of this article that the relatively bold relief of Pine Mountain and Oak Mountain in Georgia was explained by LaForge as due to the quartzites being heavier bedded there. The writer suggests another explanation. At localities one, two, and three in Alabama, the quartzites have been but recently re-exposed by the removal of the Upper Cretaceous. It is reasonable to suppose that the Upper Cretaceous beds were deposited in the Pine Mountain district. Since Pine Mountain and Oak Mountain are farther from the border of the Upper Cretaceous than the places in Alabama where the Hollis quartzites are found, it is probable that the Upper Cretaceous rocks have been removed from the localities in Georgia for a longer time. Accordingly, the prominence of

the linear ridges and knobs in Georgia is in part due to more prolonged differential weathering and erosion which have brought the resistant quartzites into strong relief in the midst of the surrounding rocks.

Pine Mountain in Georgia, together with the Hollis quartzites which are a geological continuation of it, is an interesting lineament of the crystallines, because of its position near the southern border of the area, its trend, and its relatively great length. The determination of its detailed structural relations and the satisfactory solution of the question of the age of the rocks in it are important problems to which this article is in the nature of a first contribution.

PETROLOGICAL ABSTRACTS AND REVIEWS

ALBERT JOHANNSEN

Anleitung zur chemischen Gesteinsanalyse. By J. JAKOB. "Sammlung naturwissenschaftlicher Praktika," Band XV. Berlin: Gebrüder Borntraeger, 1928. Pp. vii+81; figs. 3. Price M. 7.

This is a very handy little guide to practical rock analysis. All unnecessary theoretical material has been omitted, but the instructions necessary for the actual determinations are very fully and clearly given, so that even a beginner cannot go wrong.

What the author means by "practical" determinations is shown by the following sentences from the Preface:

> In the first place, a sharp distinction must be made between rock analysis and mineral analysis. This book treats only of the former. For rock analysis the problem is the following: How may I achieve in the shortest possible time a sufficiently accurate rock analysis? For a mineral analysis the problem is: How may I attain an analysis of the greatest possible accuracy? In the latter case the time element cannot be considered.
>
> Everyone who has had experience in rock analysis, will agree that there is no object in using methods of the greatest possible accuracy, for duplicate analyses made from the same hand specimen but from different portions show differences. That such differences always occur even when analyses are made with the greatest possible accuracy, we will frankly admit, and having recognized this, we must make a sharp distinction between rock and mineral analysis. However, this does not mean that rock analyses should be less accurate than heretofore. On the contrary, they should be more accurate than most of those now found in the literature. In this book the attempt is made to fit the accuracy of the methods to the required accuracy of determination.

The methods here given, therefore, are compromise methods, which permit, in the least possible time, the carrying-out of analyses to the utmost degree of accuracy which can or should be demanded. Several methods are sometimes given to take care of special cases. All the essentials are given in the text proper, but very extensive footnotes give explanations, further instructions, or cautions.

Elements of Optical Mineralogy. Part III: *Determinative Tables.* By N. H. WINCHELL and A. N. WINCHELL. 2d ed. New York: John Wiley & Sons, 1929. Pp. xii+204 with colored chart and two diagrams. Price $4.50.

These tables originally consisted of 49 pages and formed Part III of the first edition of this book. They have been entirely re-written and greatly enlarged by A. N. Winchell and now consist of 204 pages. Here are brought together in tabular form the data relating to the various minerals described in the second part of the series. For the transparent minerals the data are practically complete, but only a few of the commoner opaque minerals are included.

There are four sets of tables. The first (pp. 8–9) deals with the common opaque minerals, which are here divided on the same primary divisions as in the earlier edition, although the colors used for the separation have been renamed and differ slightly from those originally given.

The subdivisions of the transparent minerals were formerly based on isotropism and anisotropism. Here the primary divisions in Table II (pp. 12–75) are on the basis of birefringence. Subdivisions follow according to the refractive indices of the various minerals, making fifty-six groups, which are further subdivided on the basis of color and crystal system in the case of the isotropic crystals, and on optic sign, cleavage, extinction angle, crystal habit, $2V$, and crystal system in the anisotropic.

The third table (pp. 76–115) is based primarily on the color of the minerals in thin sections, and secondarily on pleochroism. Following these, the divisions are on birefringence, and under the groups thus formed the minerals are arranged according to their refringences. Certain other properties, such as optic character, $2V$, etc., follow each name.

The fourth table (pp. 116–73) is divided into two parts. In the first, the isotropic minerals are arranged according to increasing refringence; in the second, the anisotropic minerals are arranged according to the mean index or the index of the ordinary ray, with an indication by the column in which this value is written, whether the mineral is plus or minus. Following columns give the maximum and minimum indices, the range being shown by vertical lines to the right of the column. This table and the one following are intended primarily for use with mineral grains immersed in fluids of different refractive indices.

The fifth table (pp. 174–86) is based on the dispersion of light in minerals, that is, on the differences in refractive indices in light of F and C wave-lengths. The measurements are made on the indices of isotropic

minerals, the indices of the ordinary rays in uniaxial minerals, and the mean indices in biaxial minerals. While this table is rather incomplete, it embraces all available data. It should be especially useful when the new method of double variation comes into common use.

The plates in the pocket include a large colored reproduction of the well-known Michel-Lévy table of birefringences, and a chart showing graphically the more important minerals arranged according to refringence, birefringence, and optic sign.

This book should prove very useful in the laboratory. The author is to be congratulated on the completeness of his data.

Technische Gesteinkunde. By J. STINY. 2d ed. Vienna: Julius Springer, 1929. Pp. viii+550; figs. 422; colored plate 1. Also, in a pocket: *Kurze Anleitung zum Bestimmen der technisch wichtigsten gesteinbildenden Mineralien und Felsarten.* Pp. 23; figs. 11.

The scope of this book is indicated by the subtitle: *Für Bauingenieure, Kulturtechniker, Land- und Forstwirte, sowie für Steinbruchbesitzer und Steinbruchtechniker.* It is not, however, simply a practical handbook for engineers and quarrymen, but is a well-written and accurate petrography of building stones and building materials.

The book begins with definitions of "rock" and "petrography." These two definitions alone cover 3 pages. Various textures are defined and illustrated, and there is a long discussion of size of grain. Very briefly the process of section-grinding is described. The methods for the determination of grain sizes in various kinds of consolidated and friable rocks, as well as methods for plotting results, are given. Fifty-eight pages and 78 figures, many of them photomicrographs, are devoted to the rock-forming minerals, and there are short discussions of the technical uses, defects, advantages, and disadvantages, as well as the chemical relationships of the various kinds. Following this is a discussion of the geological mode of occurrence of the various igneous rocks, with some very good illustrations of volcanoes, etc.

Textures and structures are described in 25 pages and illustrated by 20 cuts, some of which are photomicrographs. The descriptions of the igneous rocks are brief but good as far as they go, but these necessarily could not be very complete, with only 16 pages devoted to plutonic rocks, 26 to the extrusives, and 10 to tuffs, dikes, etc. Naturally only the principal rock types are considered.

Nearly 150 pages are given to the sedimentary rocks. After a general

discussion on sediments and their properties, the subject of weathering is taken up, and this is followed by descriptions of the principal minerals of the sedimentary rocks, including chemical precipitates, limestones, etc., and of loose materials, such as loess and those which form breccias and tuffs. There are 20 pages and 37 illustrations on sandstone, 14 pages and 13 illustrations on limestone, and fewer pages on the clay rocks and rocks formed by organisms. The processes of metamorphism (pp. 329–62) and the metamorphic rocks (pp. 363–80) are briefly treated.

Part III of the book (148 pages) is devoted to the technical properties of rocks and the methods of testing them. Here are discussions of granularity, binding material, rock density, jointing, porosity, strength, workability, etc.

In the Bibliography at the end of the volume, 78 items are listed, but since no page references are given in the body of the text but simply references to certain publications in the list, many of them thick volumes, it might be hard to verify a particular statement.

The determinative tables in the back of the book, like all such tables for the megascopic determination of rocks, allow considerable chance for error. There should be an explanation of the use of the numbers.

The book is singularly free from pictures of apparatus such as usually give books of this type the appearance of instrument catalogues. It is beautifully printed, the type is clear, and in general the illustrations are excellent.

REVIEWS

Theory of Continental Drift—A Symposium. By W. A. J. M. VAN WATERSCHOOT VAN DER GRACHT, BAILEY WILLIS, ROLLIN T. CHAMBERLIN, JOHN JOLY, G. A. F. MOLENGRAAFF, J. W. GREGORY, ALFRED WEGENER, CHARLES SCHUCHERT, CHESTER R. LONGWELL, FRANK BURSLEY TAYLOR, WILLIAM BOWIE, DAVID WHITE, JOSEPH T. SINGEWALD, JR., and EDWARD W. BERRY. Tulsa, Okalhoma: American Association of Petroleum Geologists, 1928. Pp. 226; Index.

A prominent professor in a well-known eastern university, while talking to the reviewer recently, commented on the sense of shame in their profession which must have moved certain members of the American Association of Petroleum Geologists and certain oil companies to secure the publication of this book. To him it seemed a weak attempt to justify the existence of the Association. The reviewer, on the contrary, believes that its publication was a praiseworthy undertaking and a good use for surplus funds. He hopes the Association will sponsor other publications from time to time. If a sense of shame is to be identified in any way with this published collection of papers, it will probably be experienced at some time in the future by a few of the well-known contributors who have speculated so freely about the conditions within the surface of the earth.

The purpose of this book is obviously to furnish interesting reading material to the large number of field geologists in North America who do not have ready access to libraries. And it is well that this is so, for there is little here that has not already been stated elsewhere. Of the fifteen separate articles in this symposium less than half present new evidence of importance. The discussions range as widely as does the background of training and experience which the contributors bring to their task. Some view with alarm the tendency of others to disregard long-known facts; and others criticize the opposition for failure to recognize new evidence. The reader will doubtless suffer mixed emotions, as did the reviewer.

The Introduction by Dr. van der Gracht is essentially a review of the Taylor-Wegener theory, but it adduces evidences in support of this theory from the literature of isostasy, axial stability, and radioactivity. It is seventy-five pages long and unnecessarily wordy, but serves its purpose well.

Some of the contributors do not take a stand either for or against the theory, but hold out for more evidence. The article by Longwell, while it maintains a critical attitude, is outstanding in this respect.

A brief statement of the opposition is furnished by R. T. Chamberlin. Eighteen points are mentioned, many of which have been ignored by Wegener, but which nevertheless should be kept in mind in weighing the evidence for and against these newer views which postulate extreme mobility of a granitic crust. The article by Schuchert, which covers forty pages, is a complicated paleontological discussion marked by much prejudice.

As an example of the opposing viewpoints from which different men proceed to discuss the theory, it is interesting to quote William Bowie, page 184:

> Does it not seem rather strange that comparatively small masses of sial should break away from large drifting masses and be left behind? The forces that are acting on the large mass should certainly be able to keep the sial together as a unit and not permit fragments to drop off and be scattered all over the ocean areas.

And E. W. Berry, page 195:

> It is inconce vable that masses of continental size should move over such large arcs and preserve their outlines of either coast or continental margin intact.

Considerable talks about isostasy is to be found showing that the contributors are at odds in regard to its degree of "perfection." The reviewer is somewhat appalled at the lengths to which some investigators will go in attempting to support the doctrine that isostatic balance is "nearly perfect" for areas of even very small size—the word *small* usually being limited in only an indefinite way, but implying areas less than about 5,000 square miles, or 1 square degree at the equator. Geologists and geophysicists in general are quite familiar with the numerous articles by Dr. Bowie, of the United States Coast and Geodetic Survey, and the common misstatements of geological evidence, to say nothing of his own gravitational evidence, which have appeared in them. The article in this volume is somewhat less extreme but still ineffectual.

Surprising also is the stand for *belief* in nearly perfect isostatic equilibrium, taken by David White (pp. 187–88):

> Finally permit me to urge that in all considerations of any theory of continental flotation, geologists do not lose sight of the fact that isostatic equilibrium is, and presumably has been since Archean time, very much more nearly perfect than is indicated by the plus and minus (gravitational) anomalies.

The reviewer feels that this statement is subject to the same criticism that may be leveled at many articles promoting "local isostatic balance"; namely, that the terms are not satisfactorily defined. If, by "perfect" equilibrium, Dr. White means equilibrium of areas in general less than 5,000 square miles, or 1 square degree, which is the meaning usually attached to this word when used in isostatic papers, it must be pointed out that at present there is no known critical evidence, either geological or gravitational, for such a statement. A tentative generalization of the sound conclusions regarding the size of areas that may be in isostatic equilibrium should read as follows:

> There is good gravitational evidence that areas of the order of size of structural provinces and larger are in approximate isostatic equilibrium at the present time. (The structural provinces in mind are nearly the same as their superficial manifestations, the physiographic provinces as shown on the map of the United States by Fenneman and others.[1]) There seems to be no strictly geological evidence known which is out of harmony with this degree of isostatic balance, and there is some which supports it. There is neither gravitational nor geological evidence which points toward a limiting size of isostatically balanced massifs that is much smaller than the size indicated in the foregoing.

The reviewer has kept in close touch with the literature on isostasy and believes that the gravitational evidence for a condition of isostatic equilibrium in an earth crust is neither more nor less perfect than is indicated by the plus and minus anomalies, since the anomalies constitute the only gravitational evidence as yet presented.

The final article "Remarks Regarding the Papers Offered by the Other Contributors to the Symposium," written by Mr. van der Gracht, is unnecessary and detracts from the appearance of the book.

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[1] N. M. Fenneman, "Physical Divisions of the United States," *U.S. Geol. Survey Bulletin*.

Bau und Bewegung der Gebirge in Nordamerika, Skandinavien und Mitteleuropa. By HANS CLOOS. Berlin: Gebrüder Borntraeger, 1928. Pp. 85; figs. 16, pls. 5 (constituting Heft 21 of Band VII of *Fortschritte der Geologie und Palaeontologie*, edited by Professor Dr. W. Soergel). M. 14.00.

This book is a significant attempt to utilize the "much neglected" major zones of normal faulting inductively for the recognition of larger stress relations and to connect them genetically with the larger deformation of the orogenic belts. The following regions form the basis of this study: the en echelon faults of Oklahoma; the fault zone of the Jura Plateau east of Basel; the faults of the western Great Basin along the east front of the Sierra Nevada; the system of faults of the Coast Ranges; the graben district of the Christiania fjord; the belt of Tertiary volcanic activity in Scotland and Ireland; the major tectonic lines of Central Europe.

Cloos's interpretation is the outgrowth of his detailed observations on the relation of fractures to lines of flow in intrusives. In a valuable introductory chapter his generalizations concerning intrusives are summarized on the basis of observations made in the Yosemite region jointly with Dr. Balk. The introduction is continued in a chapter devoted to observations on the details of deformation on the edge of a graben in the Christiania region. It is intended to show that the pattern of fractures and other indications of strain devoloped in sedimentary rocks through the drag in fault movements is comparable to that observed as the result of retarded flow along the contact of an intrusive mass. Brief comments on the fractures observed in flowing masses of clay and in drifting ice blocks close the introductory portion.

Cloos views the relation of regions of normal fracturing to the belts of folding in the light of his studies of the effects of deformation attending viscous flow. He transfers the phenomena from a vertical to a horizontal plane. To him the arcuate pattern of mountain folds is the counterpart of the curved alignment of *Schlieren* inclusions in a granite intrusive. Both are the result of differential flow. Cloos compares the folds of a system like that of the Ouachitas or the Jura Mountains to wrinkles in the scum covering the surface of a brook. The strike of the mountain wrinkles indicates the trend of a deep-seated, slow, viscous flow dragging with it a thin inert crust.

Cloos tries to show that the pattern of the fault zones which he discusses can be interpreted as the product of the same "current" that is responsible for the neighboring mountain folds. He regards en echelon

fractures as diagnostic of differential movement involving flow. Other possible factors and forms of strain that may produce identical fracture patterns are not considered. His term "*Fiederspalten*," "barbed fractures," comprises, in addition, all cases in which two systems of fractures meet or intersect at acute angles. Under this comprehensive term the faults of the Coast Ranges and of the contact of the Great Basin and the Sierra Nevada are classed by Cloos, as well as the essentially parallel faults of the Jura Plateau and the long, narrow belts of en echelon faults in Oklahoma.

In the latter two cases, the belts of faulting are parallel to the direction of the subcrustal flow inferred from the strike of the folds in the Ouachita and Jura Mountains. In Western United States they stand at right angles to the strike of the orogenic structures. This contrast Cloos explains by assuming that the subcrustal "current" in its impact against the continental mass of North America is split into two components, one diving beneath the continent, the other running parallel with it. The former, dragging the crust down with it, causes the westward thrusts; the latter accounts for the fault patterns of California and Nevada. Similar reasoning is applied to Western Europe.

One is reminded of Argand's praise of the "*extrême flexibilité jointe à une grande richesse en tours opératoires*" of Wegener's hypothesis, a flexibility that defies all objections with the "*résistance protéenne d'un univers plastique.*" (*Congr. Géol. Int., Compt. Rend., XIII^e session, 1922*, I, 292). Perhaps the truth concerning the causes of orogenesis lies in the direction of some *tectonique en mouvement*, such as dominates tectonic thought at present among Swiss, German, and Dutch geologists. Some of us remain to be convinced. We are at any rate grateful for the broadening of the vista of possibilities of interpretation which results from such first sketches of hypothesis.

Cloos begins and ends his regional discussion with countries in which active deformation is observed by geodetic means. He lays great stress on the coincidence of the direction of flow inferred and of deformation observed in California and Bavaria.

WALTER H. BUCHER